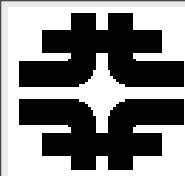


A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
Fermilab
for the Mu2e Collaboration



R.M. Carey, K.R. Lynch, J.P. Miller*, B.L. Roberts
Boston University

W. Marciano, Y. Semertzidis, P. Yamin
Brookhaven National Laboratory

Yu.G. Kolomensky
University of California, Berkeley

C.M. Ankenbrandt, R.H. Bernstein*, D. Bogert, S.J. Brice, D.R. Broemmelsiek, R. Coleman, D.F. DeJongh, S. Geer, R. Kutschke, M. Lamm, M.A. Martens, S. Nagaitsev, D.V. Neuffer, M. Popovic, E.J. Prebys, M. Syphers, R.E. Ray, H.B. White, K. Yonehara, C.Y. Yoshikawa
Fermi National Accelerator Laboratory

D. Dale, K.J. Keeter, E. Tatar
Idaho State University

W. Molzon
University of California, Irvine

P.T. Debevec, G. Gollin, D.W. Hertzog, P. Kammler
University of Illinois, Urbana-Champaign

F. Cervelli, R. Carosi, M. Incagli, T. Lomtadze, L. Ristori, F. Scuri, C. Vannini
Istituto Nazionale di Fisica Nucleare Pisa, Università Di Pisa

V. Lobashev
Institute for Nuclear Research, Moscow, Russia

D.M. Kawall, K.S. Kumar
University of Massachusetts, Amherst

R.J. Abrams, M.A.C. Cummings, R.P. Johnson, S.A. Kahn, S.A. Korenev, T.J. Roberts, R.C. Sah
Muons, Inc.

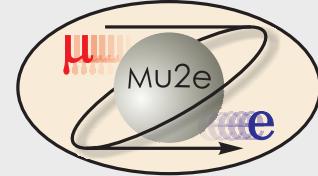
J.L. Popp
City University of New York, York

A. DeGouvea
Northwestern University

M. Corcoran
Rice University

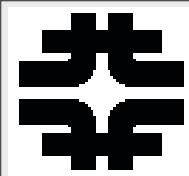
R.S. Holmes, P.A. Souder
Syracuse University

M.A. Bychkov, E.C. Dukes, E. Frlez, R.J. Hirosky, A.J. Norman, K.D. Paschke, D. Pocanic
University of Virginia

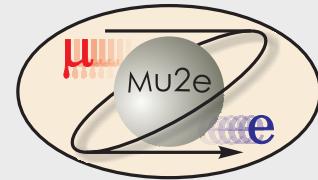


Collaboration

**64 collaborators
16 institutions**



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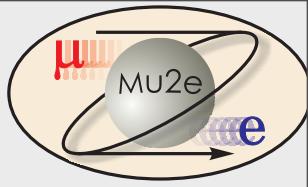
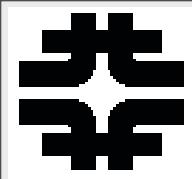
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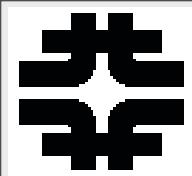
added since June 2008
now international

64 collaborators
16 institutions

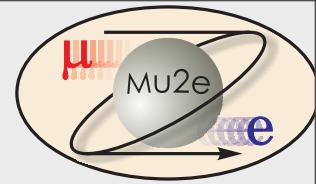


Outline

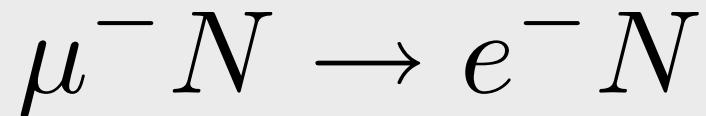
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



What is μe Conversion?



muon converts to electron in the presence of a nucleus



$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

- Charged Lepton Flavor Violation (CLFV)
- Related Processes:

μ or $\tau \rightarrow e\gamma$, e^+e^-e , $K_L \rightarrow \mu e$, and more



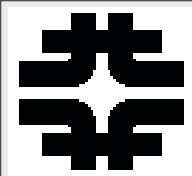
Endorsed in US Roadmap

FNAL has proposed muon-electron conversion as a flagship program for the next decade

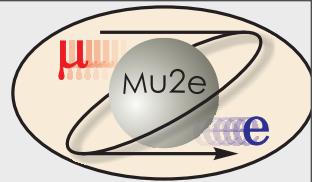
Strongly endorsed by P5:

“The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. **The panel recommends pursuing the muon-to-electron conversion experiment... under all budget scenarios considered by the panel**”

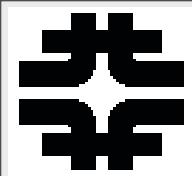
Mu2e is a central part of the future US program



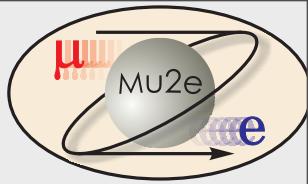
News!



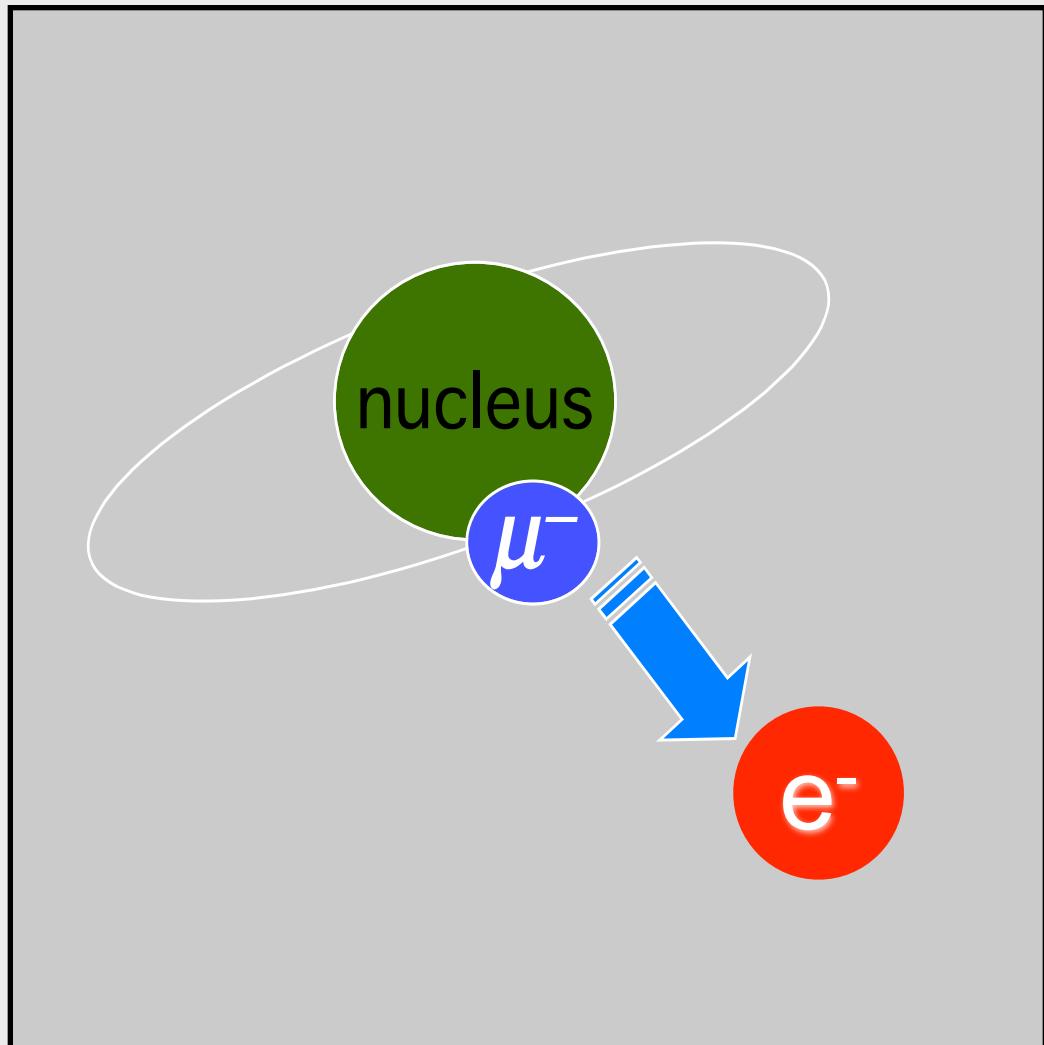
- Recommended for Approval by Fermilab Physics Advisory Committee (PAC) last week!
- Letter was read to us Monday night 11 Nov
- This is terrific news and Deputy Director told us experiment is “on track”
- *Fermilab supports the experiment*

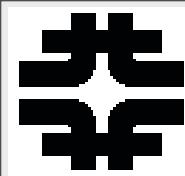


Experimental Signal

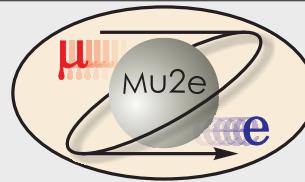


- A Single Monoenergetic Electron
- If $N = Al$, $E_e = 105.$ MeV
 - electron energy depends on Z





“Who ordered that?”

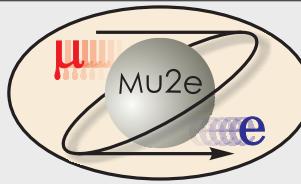
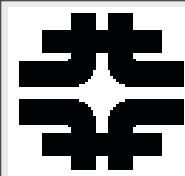


– I.I. Rabi, 1936

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν , in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

→ same as GIM mechanism!



“Who ordered that?”



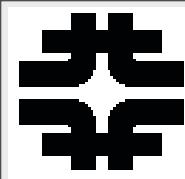
– I.I. Rabi, 1936

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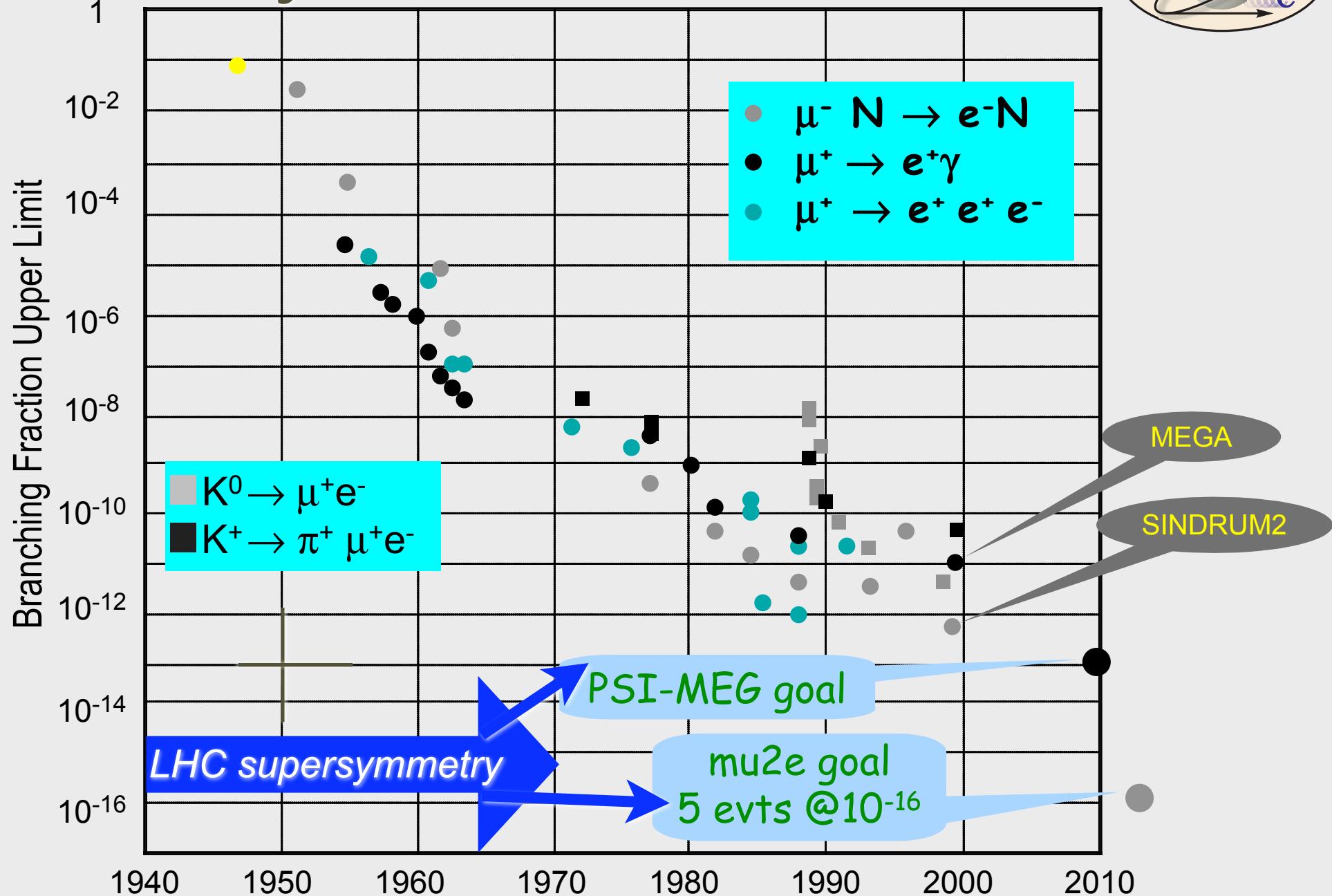
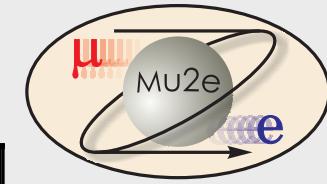
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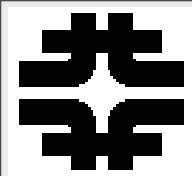
→ same as GIM mechanism!

¹Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

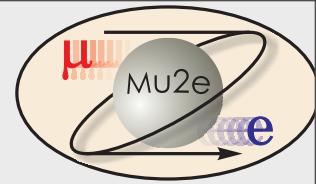


History of CLFV Searches

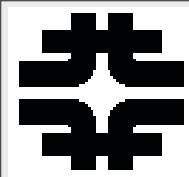




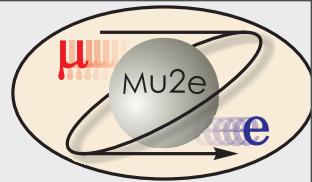
Current and Planned Lepton Flavor Violation Searches



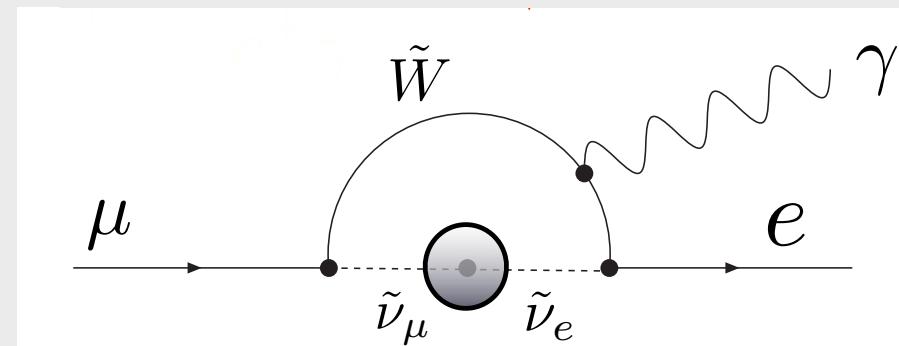
- Neutrino Oscillations!
- CLFV in SUSY
- LFV current limits at $\tau \rightarrow \mu\gamma$ and $B^0 \rightarrow \mu e$
- MEG and $\mu \rightarrow e\gamma$
- Mu2e:
 - Strengths of muon-electron conversion
 - Complementarity to other processes



Neutrino Oscillations and Muon-Electron Conversion



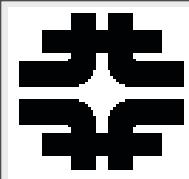
- ν 's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



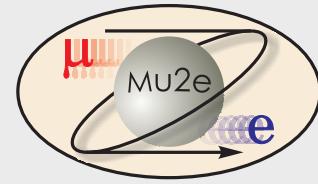
$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

:(

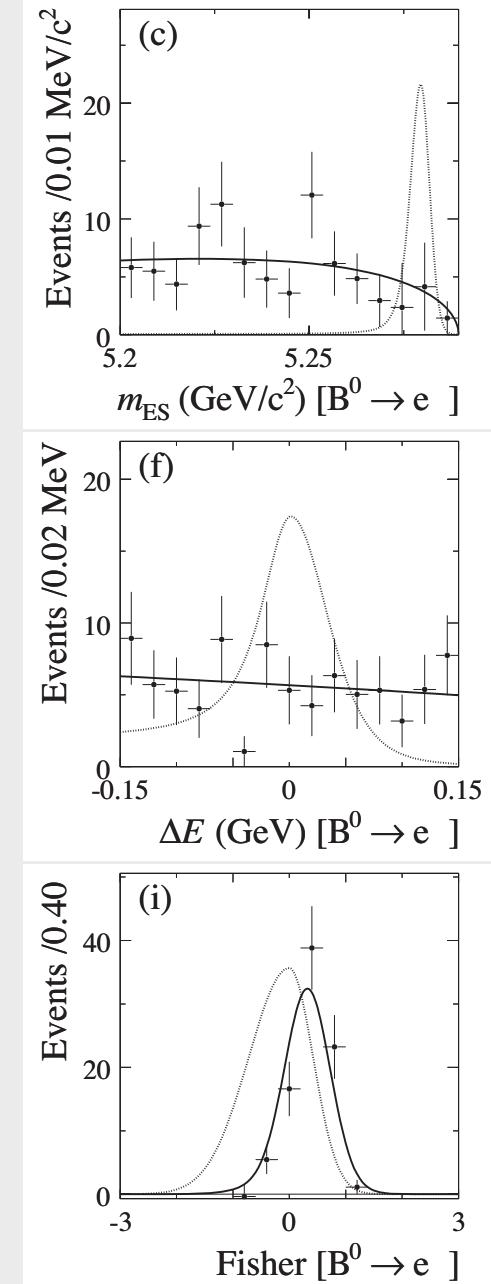
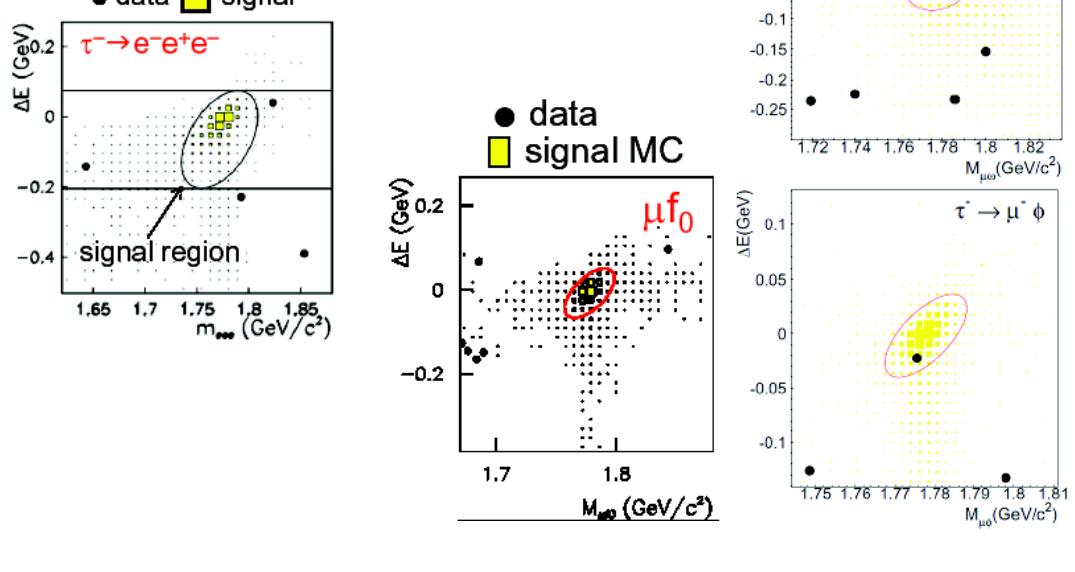
10^{-52} for μe conversion



Lepton Flavor Violation

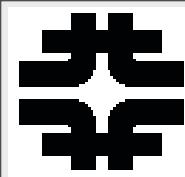


τ LFV at Belle

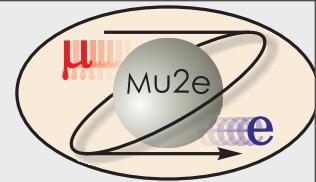


BABAR
Pub-07057
 $< 9 \times 10^{-8}$

Belle and BABAR

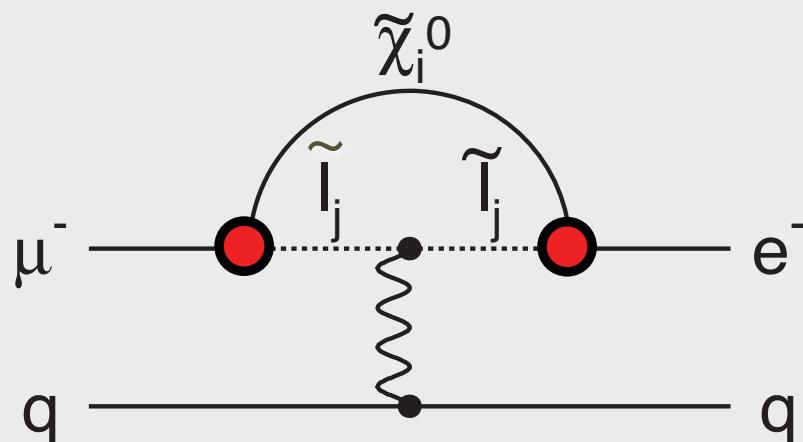


LFV, SUSY and the LHC



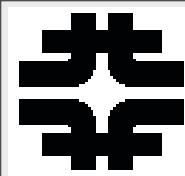
Supersymmetry

rate $\sim 10^{-15}$

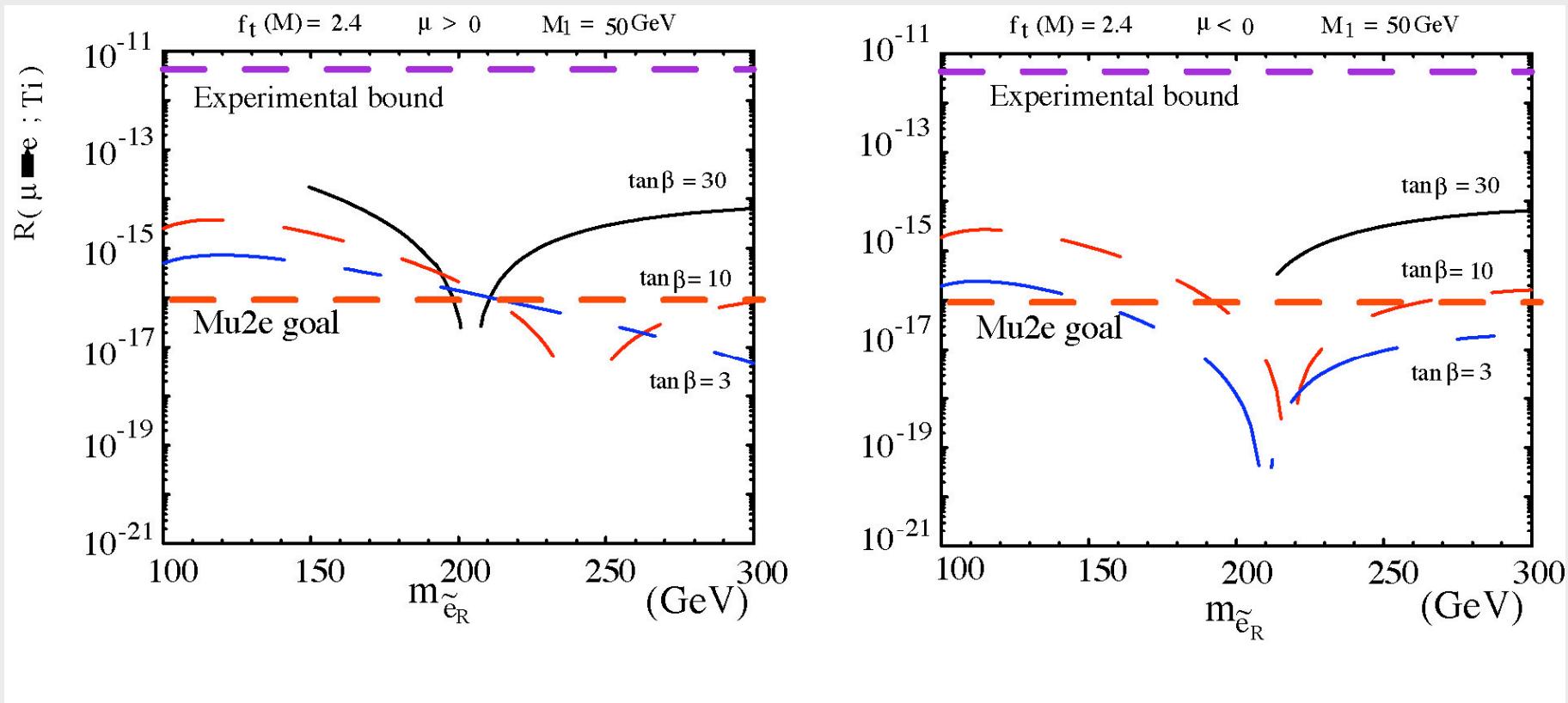
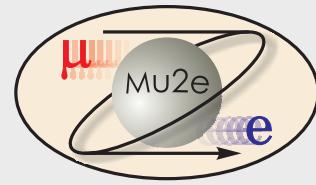


**Access SUSY
through loops:**

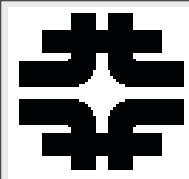
*signal of
Terascale at LHC
implies
~40 event signal /
0.4 bkg in this
experiment*



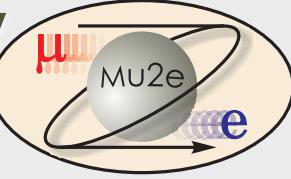
Supersymmetry and Mu2e in Minimal SU(5)



J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B 391, 341 (1997).
[Erratum-ibid. B397, 357 (1997).]

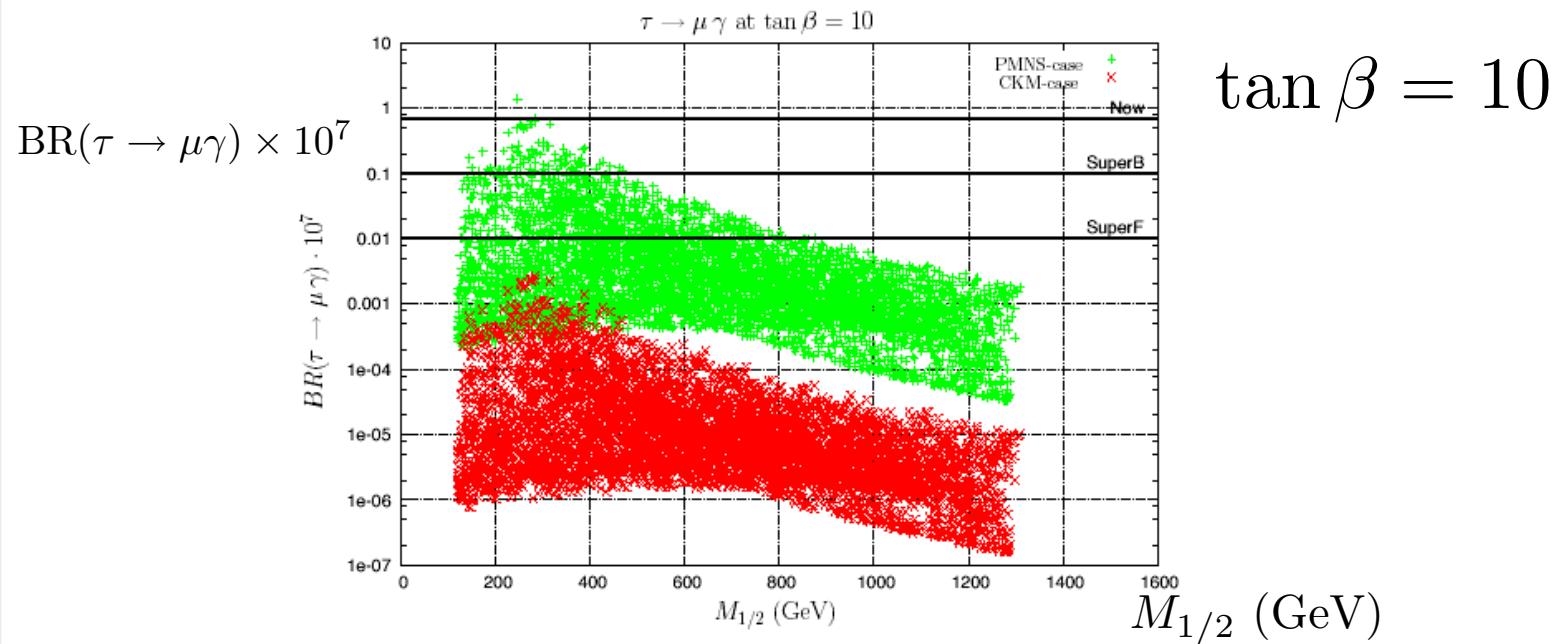


Supersymmetry in Tau LFV



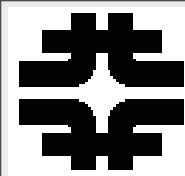
L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

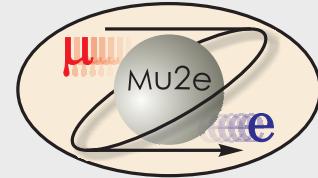


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

neutrino mass via the see-saw mechanism, analysis is performed in an SO(10) framework



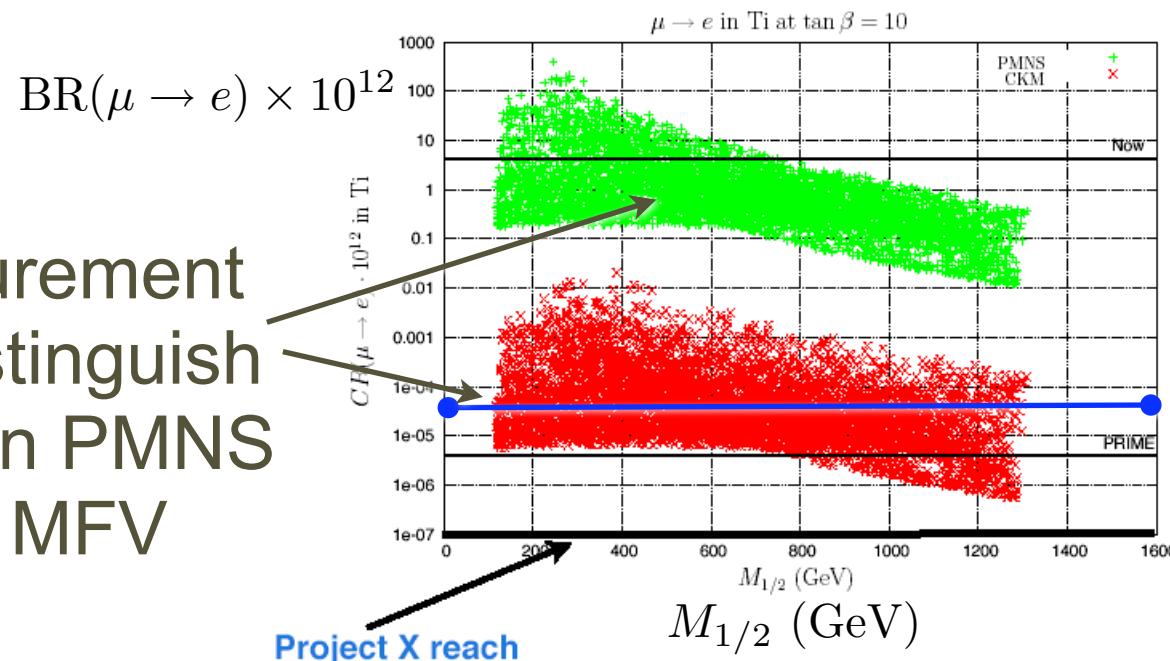
And Muon-Electron Conversion



$$\tan \beta = 10$$

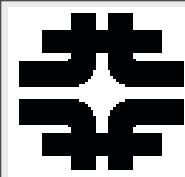
Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

measurement
can distinguish
between PMNS
and MFV

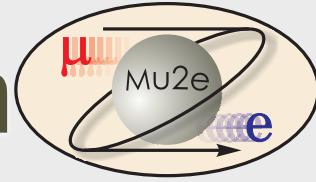


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

complementarity between Lepton Flavor Violation (LFV) and LHC experiments!

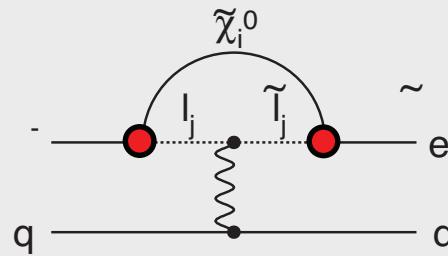


Contributions to μe Conversion



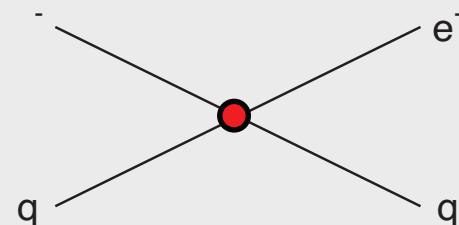
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rate $\sim 10^{-15}$



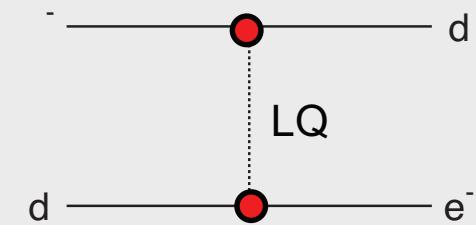
Compositeness

$\Lambda_c \sim 3000$ TeV



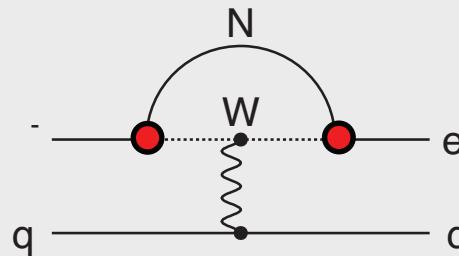
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$$



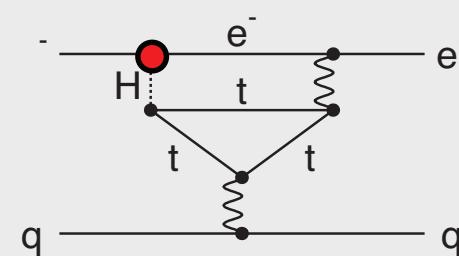
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



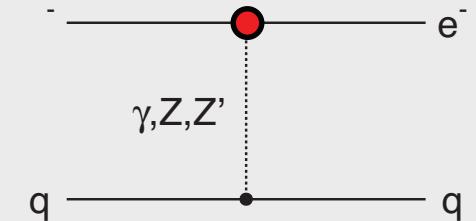
Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$$

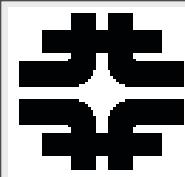


Heavy Z' Anomal. Z Coupling

$$M_{Z'} = 3000 \text{ TeV}/c^2$$



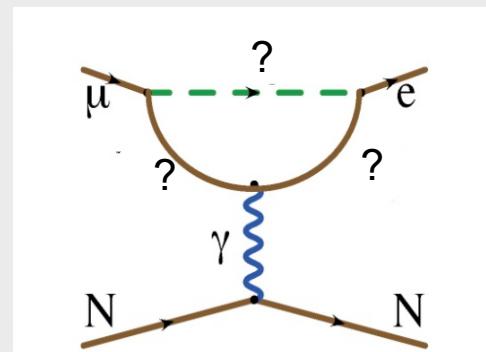
also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)



“Model-Independent” Picture

$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

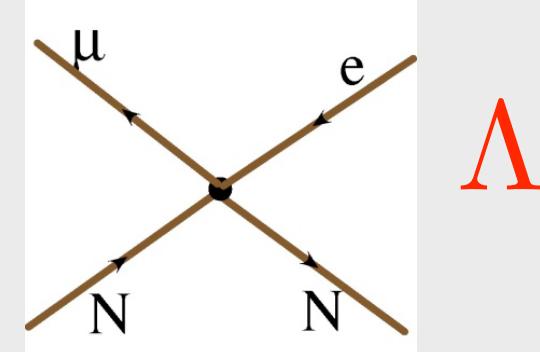
“Loops”



Supersymmetry and Heavy Neutrinos

Contributes to $\mu \rightarrow e\gamma$

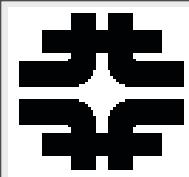
“Contact Terms”



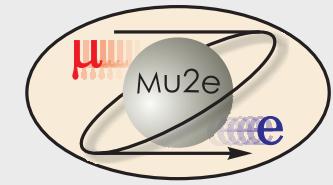
Exchange of a new, massive particle

Does not produce $\mu \rightarrow e\gamma$

Quantitative Comparison?

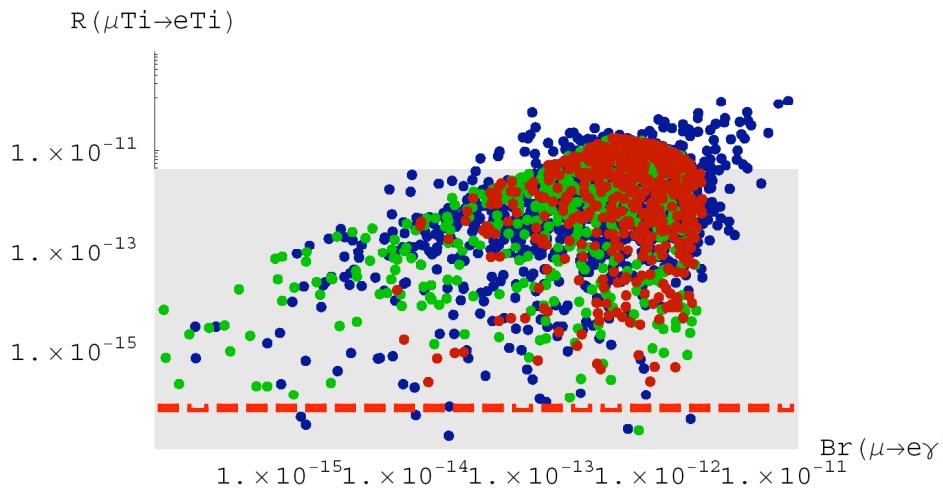


Combining $\mu \rightarrow e\gamma$ with $\mu \rightarrow e$ Conversion



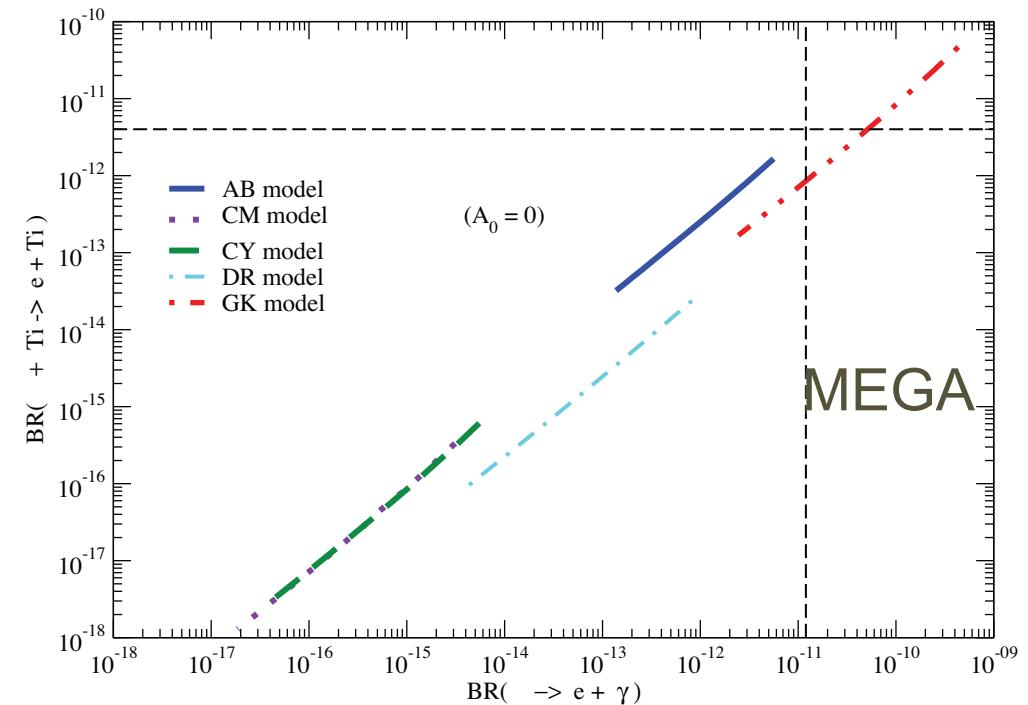
Randall-Sundrum

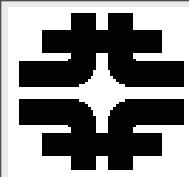
M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).



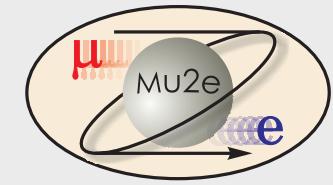
SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.



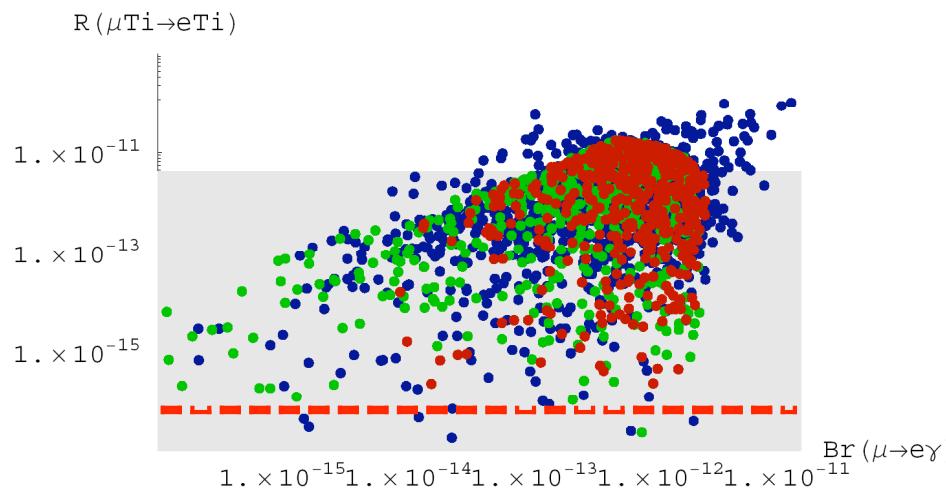


Combining $\mu \rightarrow e\gamma$ with $\mu \rightarrow e$ Conversion



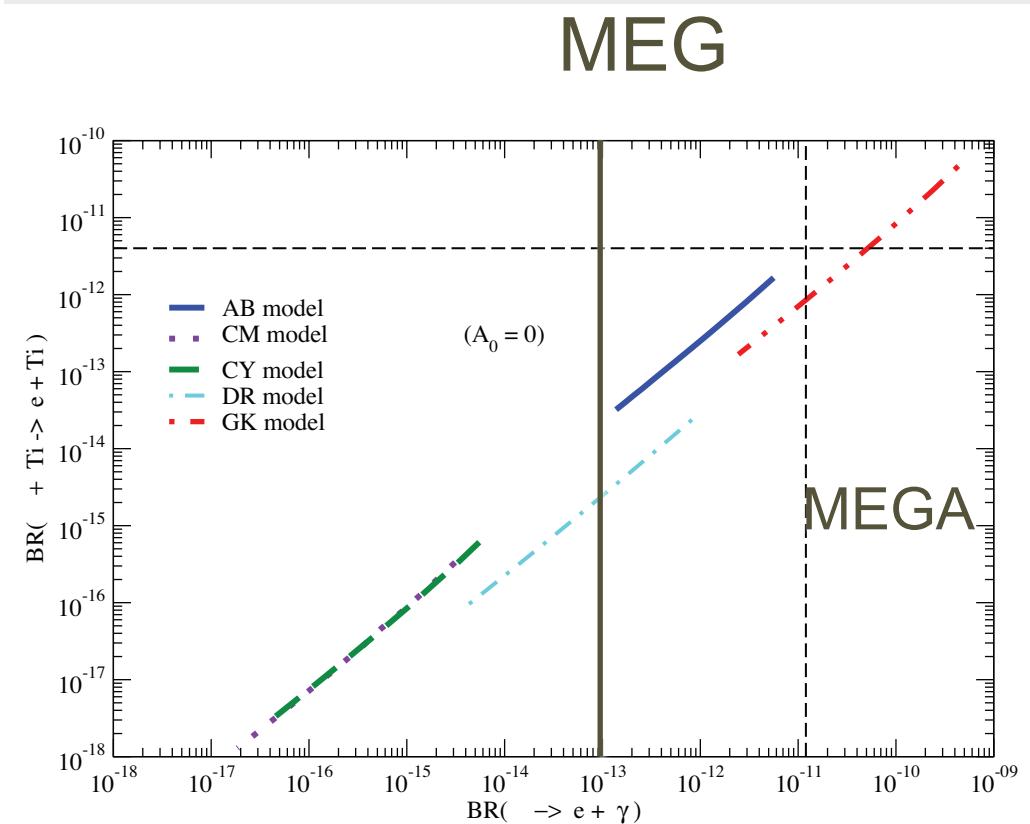
Randall-Sundrum

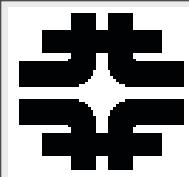
M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).



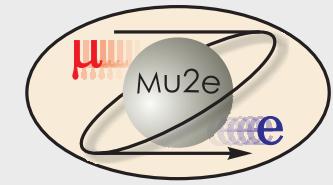
SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.



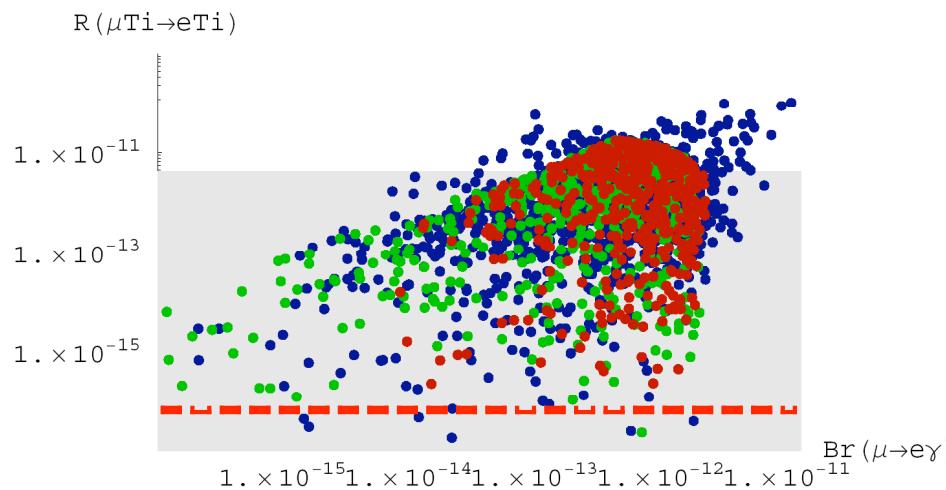


Combining $\mu \rightarrow e\gamma$ with $\mu \rightarrow e$ Conversion



Randall-Sundrum

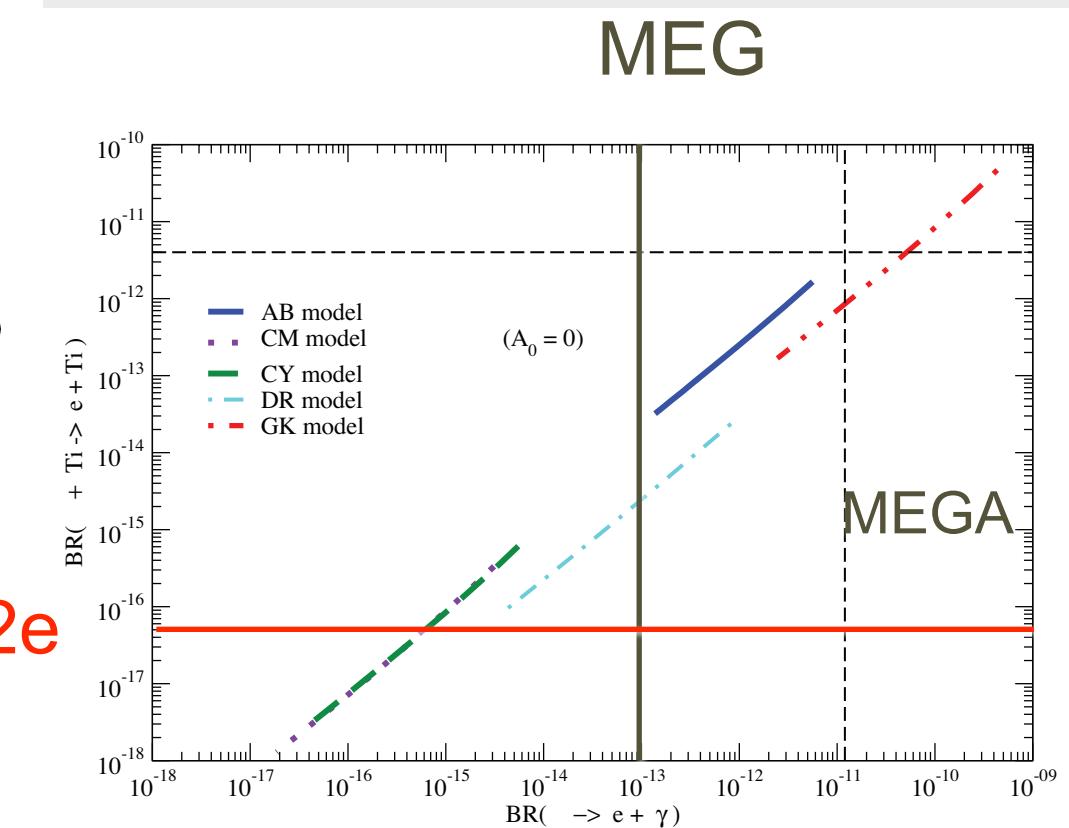
M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).

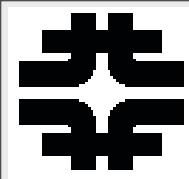


SO(10) models:

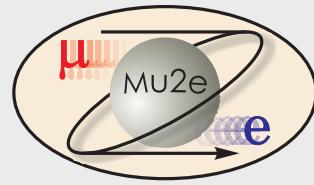
C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

Mu2e



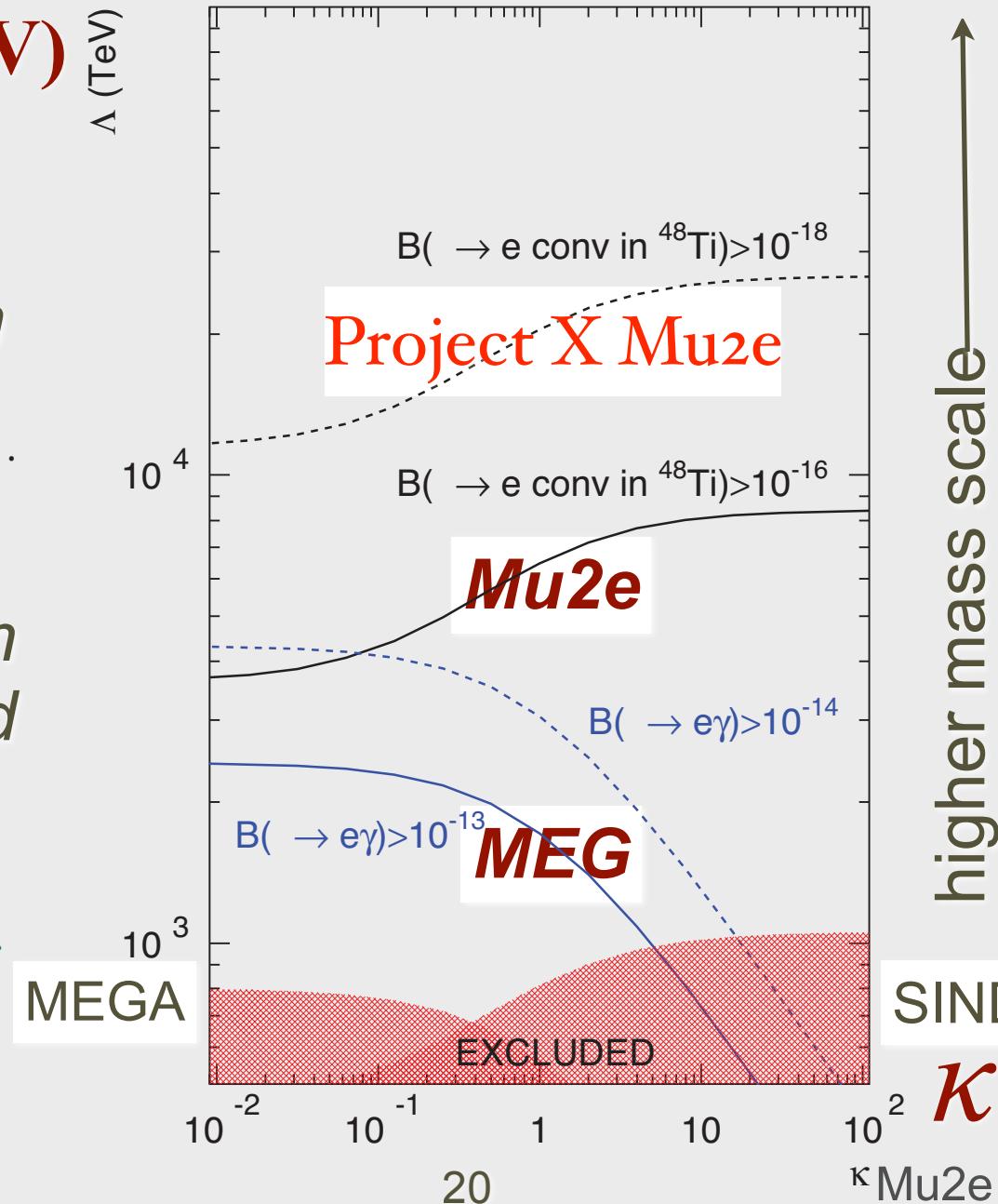


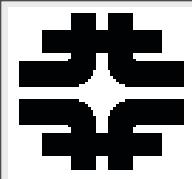
μe Conversion and $\mu \rightarrow e\gamma$



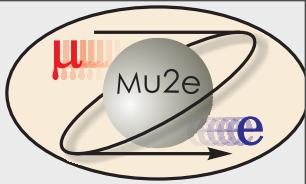
1) Mass Reach
to $\sim 10^4$ TeV

2) about x2
beyond MEG in
loop-dominated
physics

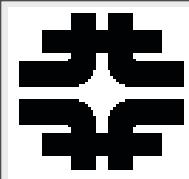




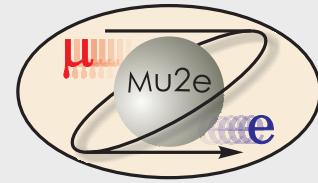
Outline



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Overview Of Processes

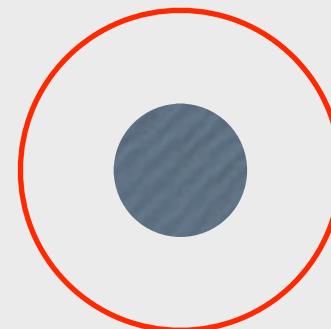


μ^- stops in thin Al foil



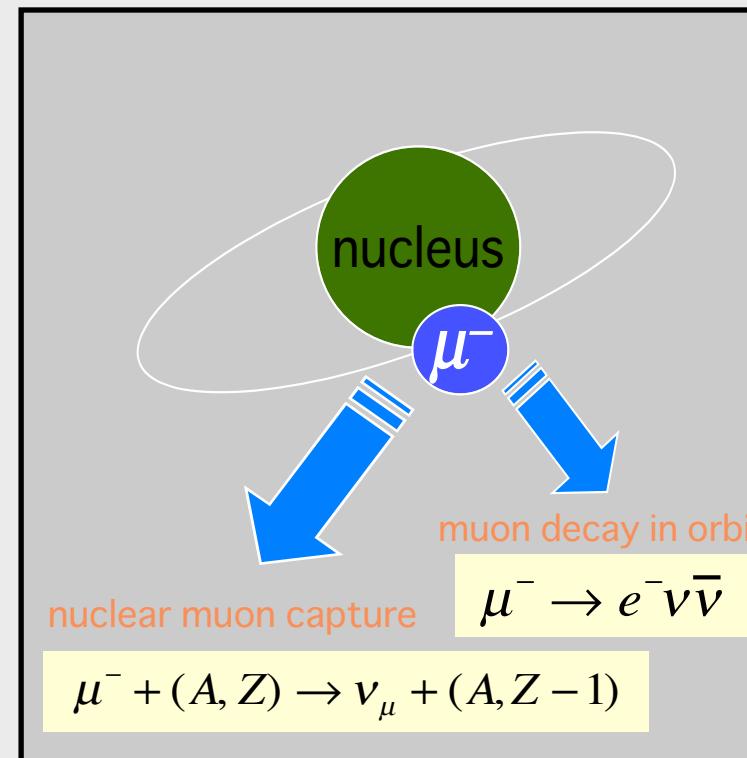
*the Bohr radius is $\sim 20 \text{ fm}$,
so the μ^- sees the nucleus*

μ^- in 1s state



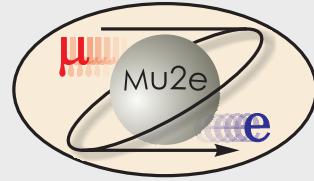
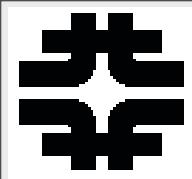
Al Nucleus
 $\sim 4 \text{ fm}$

muon capture,
muon “falls into”
nucleus:
normalization



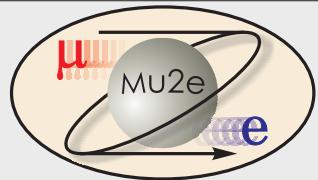
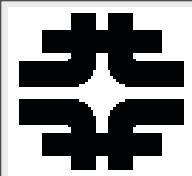
60% capture
40% decay

Decay in Orbit:
background



Two Classes of Backgrounds

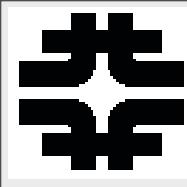
	Prompt	Decay-In-Orbit
Source	Mostly π 's produced in target	Physics Background nearly indistinguishable from signal
Solution	Design of Muon Beam, formation, transport, and time structure	Spectrometer Design: resolution and pattern recognition



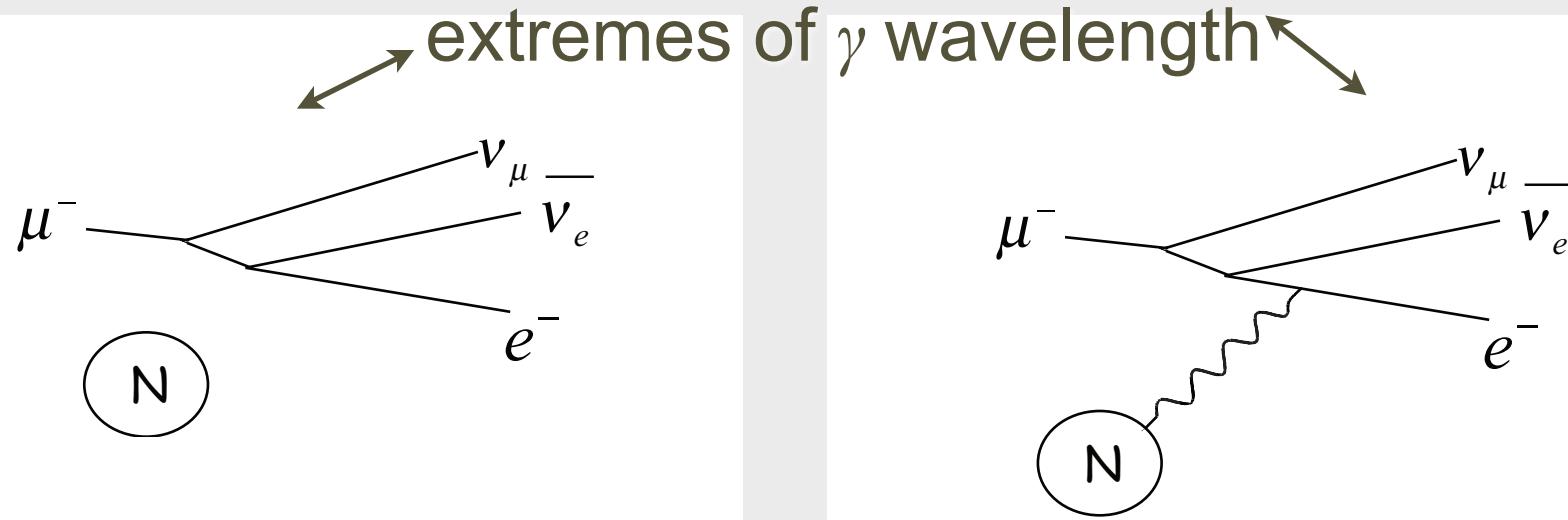
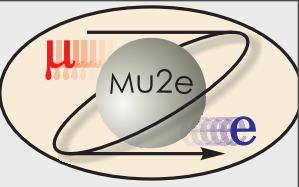
Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π , neutrons, pbars

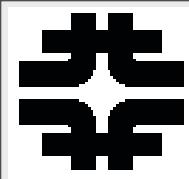
- Radiative pion capture, $\pi^- + A(N, Z) \rightarrow \gamma + X$.
 - γ up to m_π , peak at 110 MeV; $\gamma \rightarrow e^+ e^-$; if one electron ~ 100 MeV in the target, looks like signal: ***limitation in best existing experiment, SINDRUM II?***
- Beam electrons: incident on the stopping target and scatter into the detector region. Need to suppress e^- with $E > 100$ MeV near 105 MeV signal
- In-flight muon decays yielding electrons: if they decay with momentum > 76 MeV/c, can yield electron in signal region



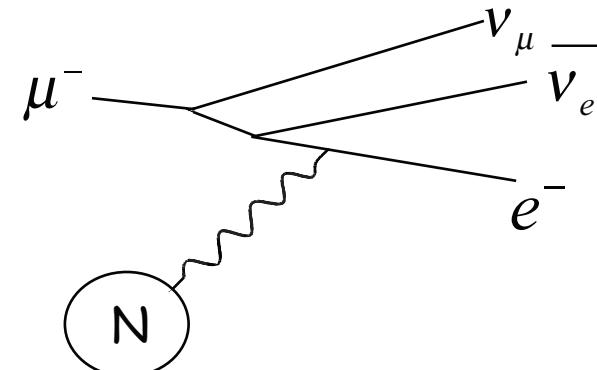
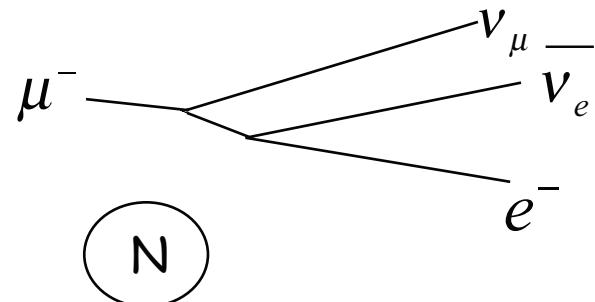
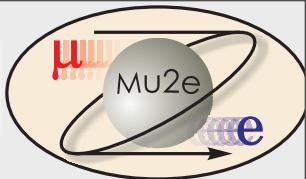
Decay-in-Orbit Background



- High Rate
- Peak 52.8 MeV
- Detector insensitive to electrons at this energy
- *Zero energy neutrinos and coherent scatter off nucleus put DIO's at conversion energy*
- Rate falls as $(E_{\text{max}} - E)^5$
- Fraction within resolution of signal $< 10^{-17}$

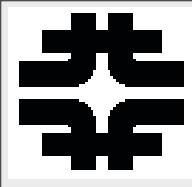


Decay-in-Orbit Background

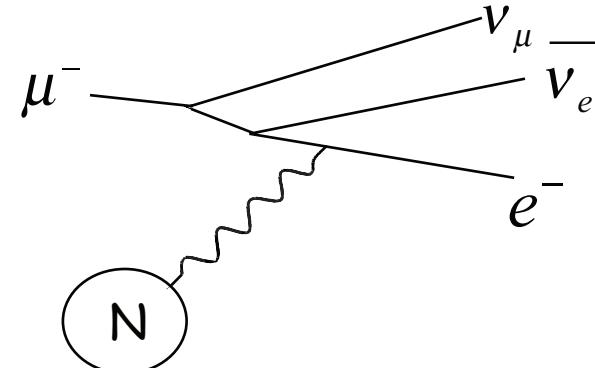
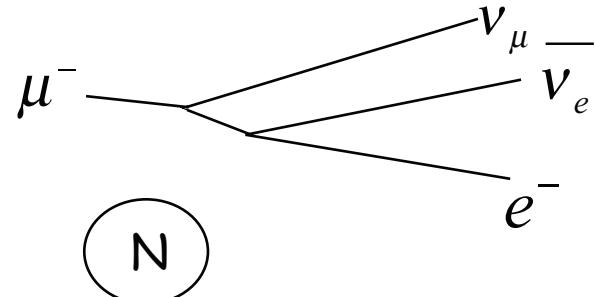
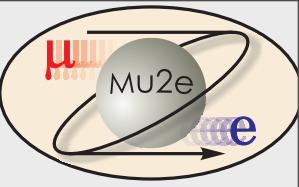


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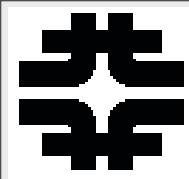
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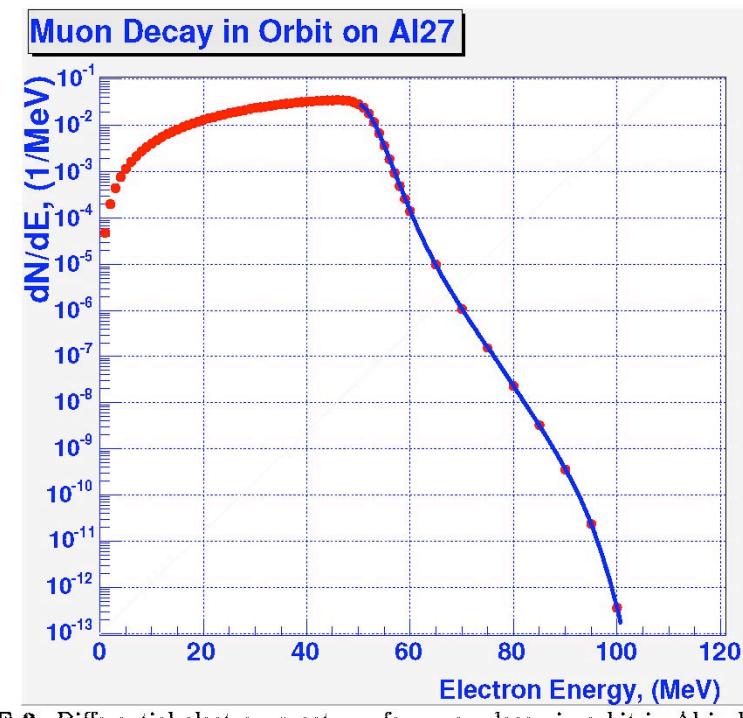
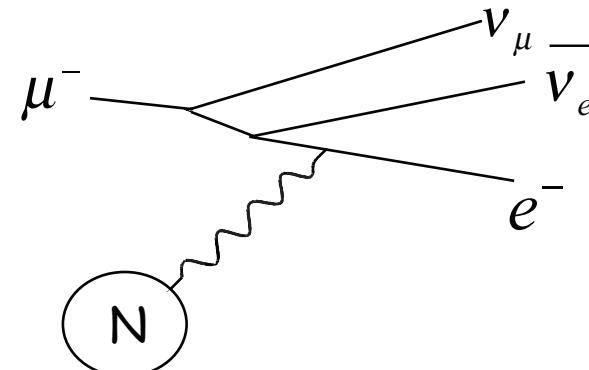
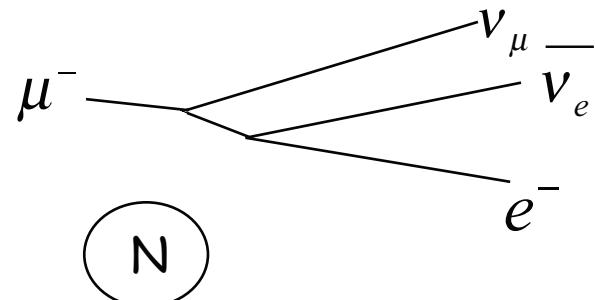
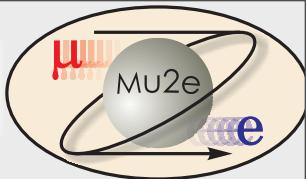
Decay-in-Orbit Background



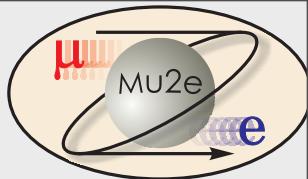
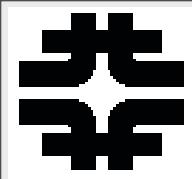
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Decay-in-Orbit Background

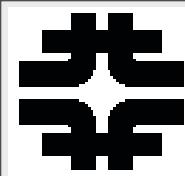


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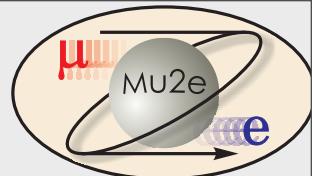


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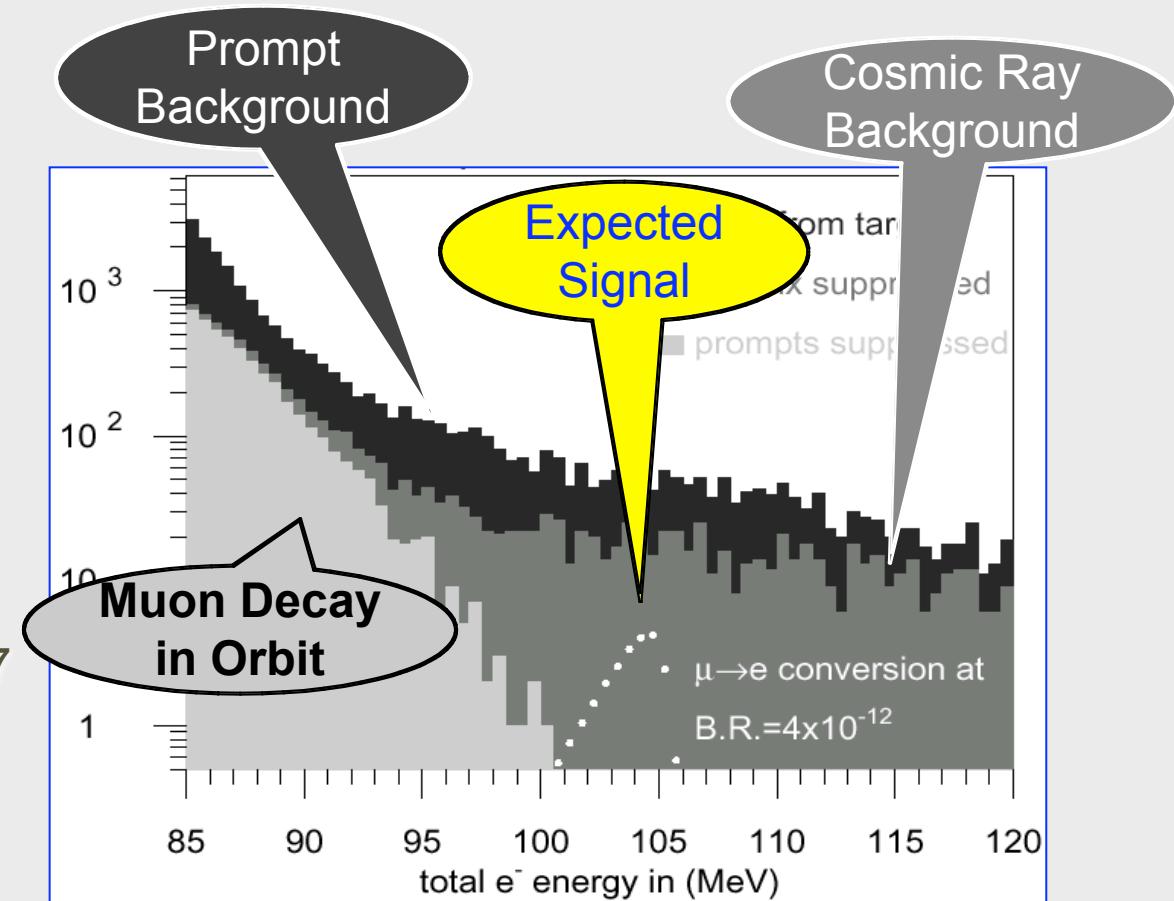


Previous Best Experiment

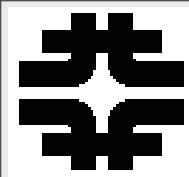


SINDRUM-II

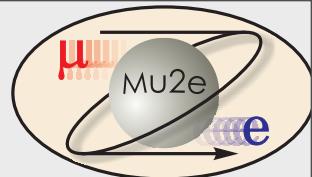
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



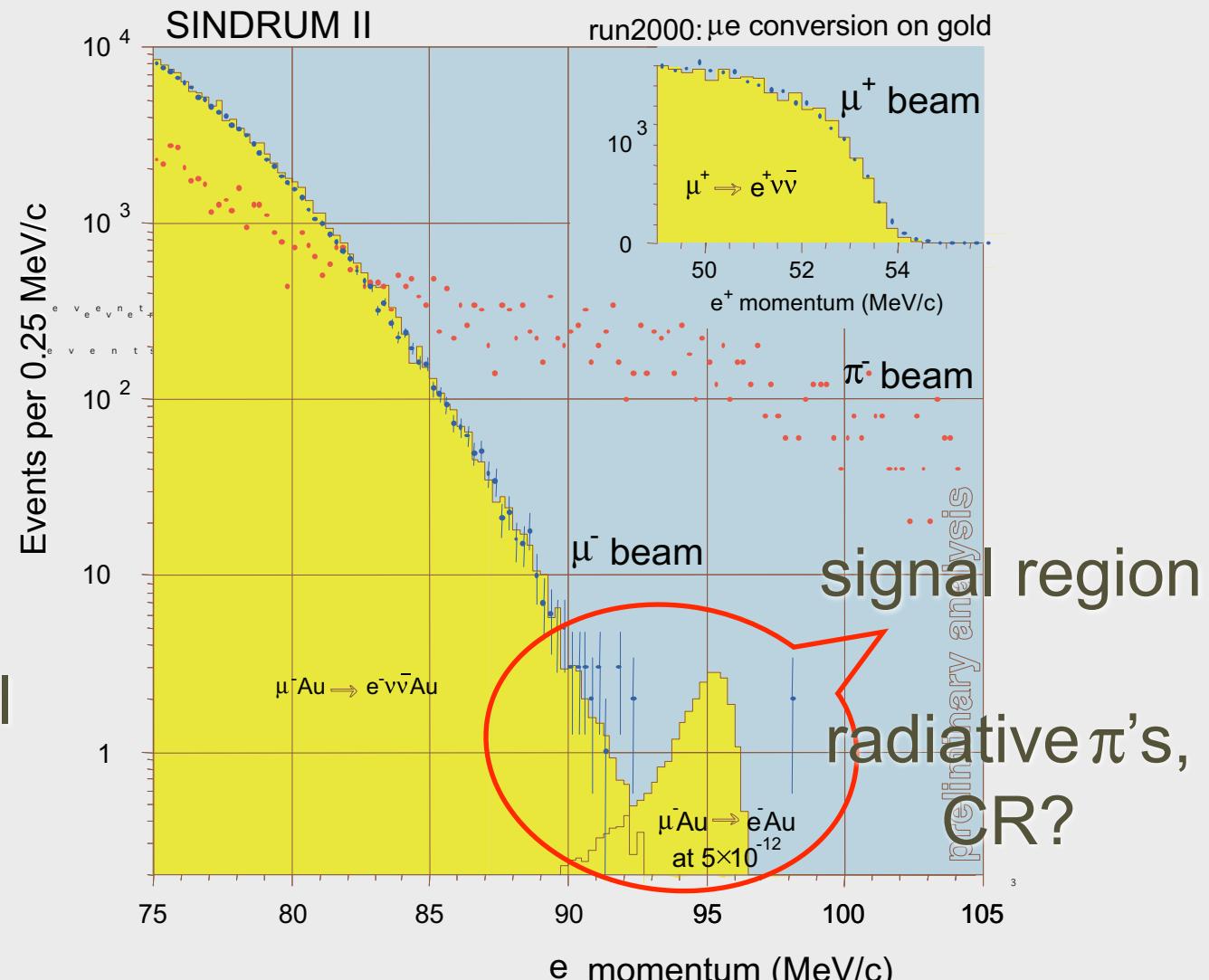
Experimental signature is 105 MeV e^- originating in a thin Ti stopping target



SINDRUM II Results



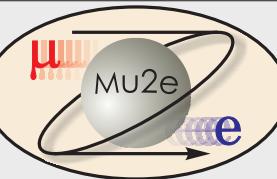
- Final SINDRUM-II on Au
- Note Two Background Events past Signal Region



W. Bertl et al, Eur. Phys. J. C **47**, 337-346 (2006)

July 14, 2001

HEP 2001 (W.Bertl - SINDRUM II collaboration)



What Limited SINDRUM-II?

DC Beam

no time separation
between
signal and prompt
background

radiative π capture

Background : b) pion induced

Radiative Pion Capture (RPC) : $\pi^- Au \rightarrow \gamma + Pt^*$ followed by $\gamma \rightarrow e^+ e^-$

Kinematic endpoint of photon spectrum around 130 MeV ! Branching ratio of order 2%.

No way to distinguish an asymmetric $e^+ e^-$ -pair (with little e^+ energy and e^- energy at 95 MeV) from μe !

⇒ Needs strong pion suppression : only ~ 1 pion every 5 minutes is allowed to reach gold target!

⇒ tune beamline to suppress high momentum tail

⇒ use degrader 8m in front of gold target to separate μ 's and π 's by their different stopping power. Penetrating slow pions decay in PMC.

positron distributions

$E / 75 \text{ MeV}$

$dz(\text{cm})$

d

z

20

0

-20

-40

-60

0

5

10

15

20

$r.f. \text{ phase (ns)}$

4024

$ENTRIES$

75

25

0

-25

-50

70

80

90

100

$E (\text{MeV})$

$in \text{ phase}$

989

$ENTRIES$

$July 14, 2001$

BUT: Degrader is now pion stop target → $e^+ e^-$ pairs from RPC are collected by B_{PMC} and transported towards the gold target where they may scatter into spectrometer acceptance (typ. forward scattering)

⇒ use solid angle and cyclotron phase correlation to cut.

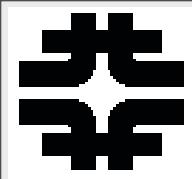
$\pi E5$

PMC

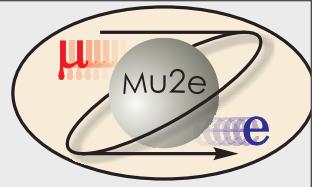
$SINDRUM$

HEP 2001 (W.Bertl - SINDRUM II collaboration)

cosmic rays also near-limiting for DC beam



How Can We Do Better?

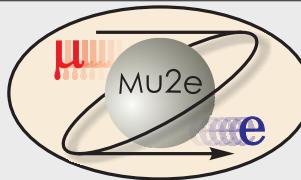


>10³ increase in muon intensity from SINDRUM

Requiring

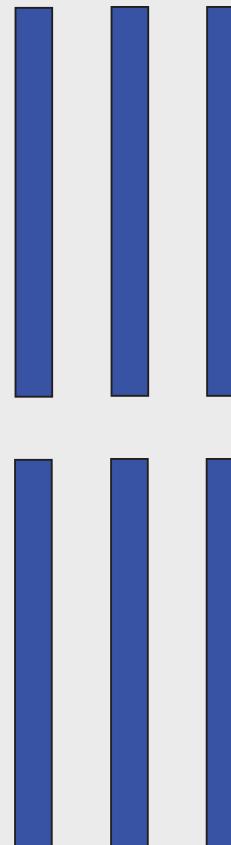
Pulsed Beam to Eliminate prompt backgrounds like
radiative π capture and CR

protons out of beam pulse/ protons in beam-pulse < 10⁻⁹
and we must measure it



Advantage of Pulsed Beam

target foils: muon converts here



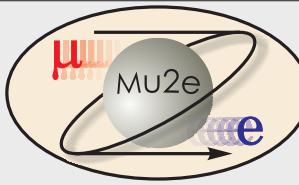
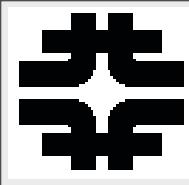
 = muons, electrons, pions

Recall:

Muon-electron
conversion signal is a

**single, monoenergetic
electron**

pulsed beam lets us
wait until after prompt
backgrounds
disappear



Advantage of Pulsed Beam

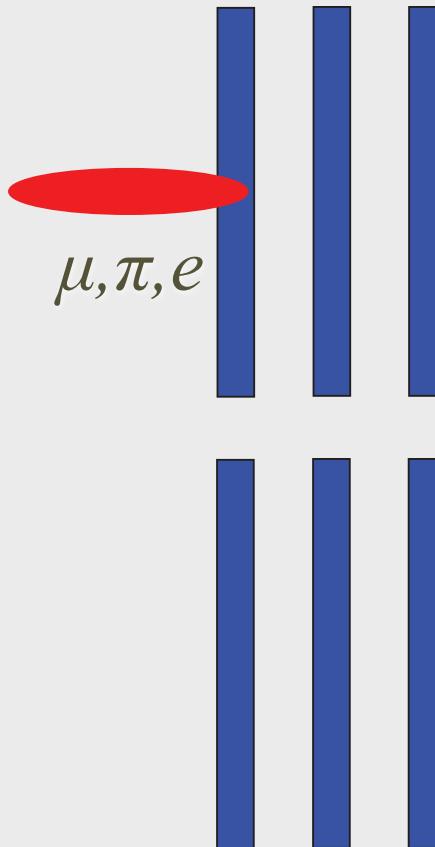
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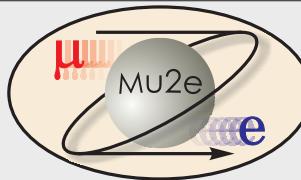
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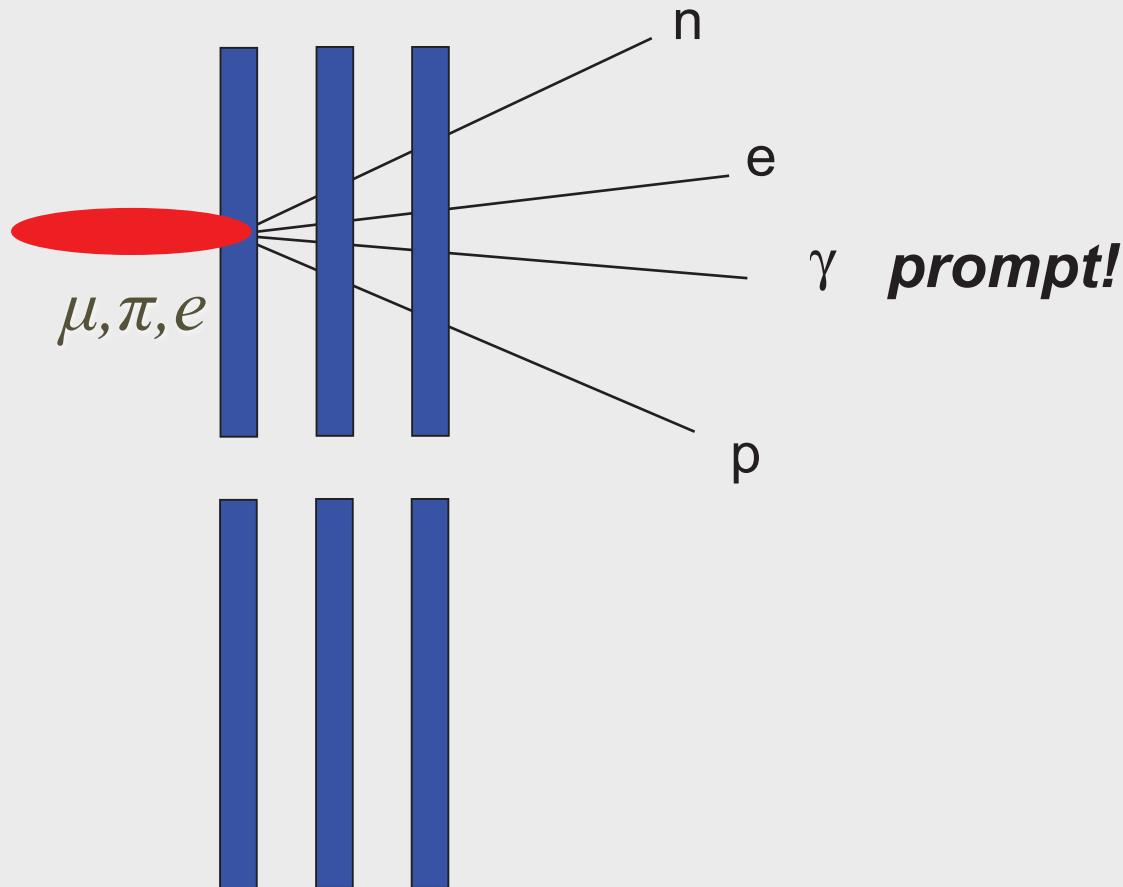
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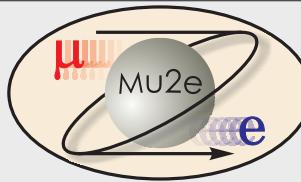
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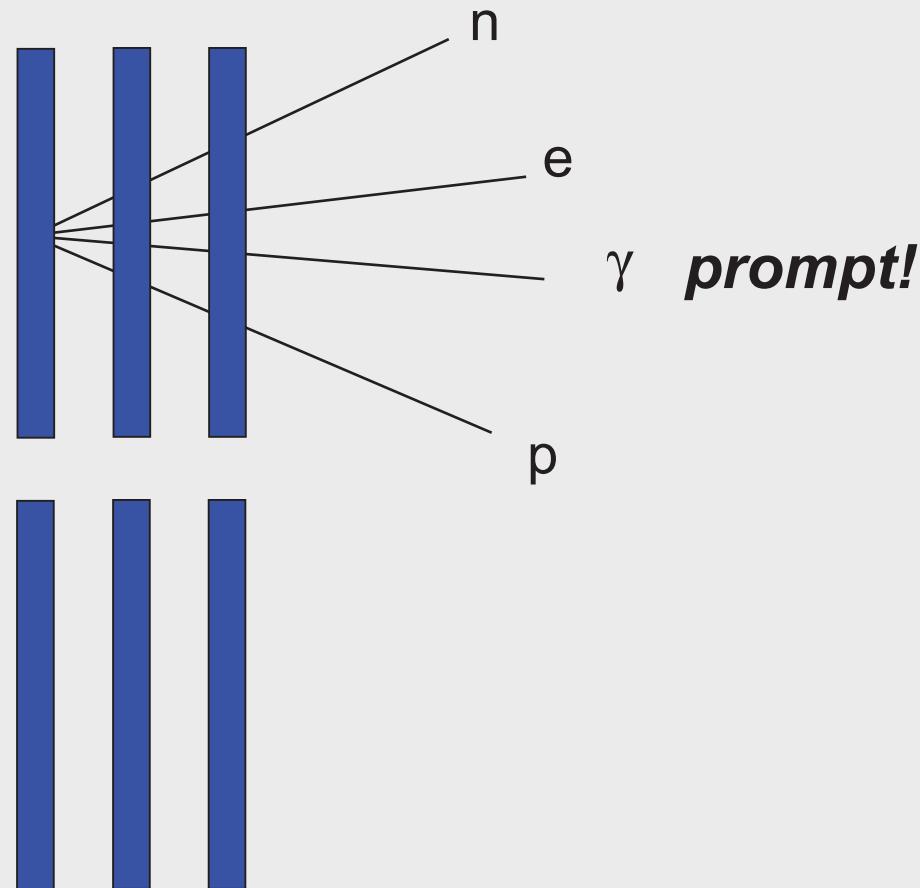
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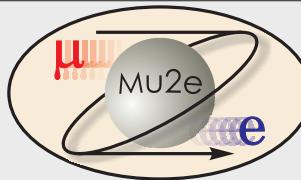


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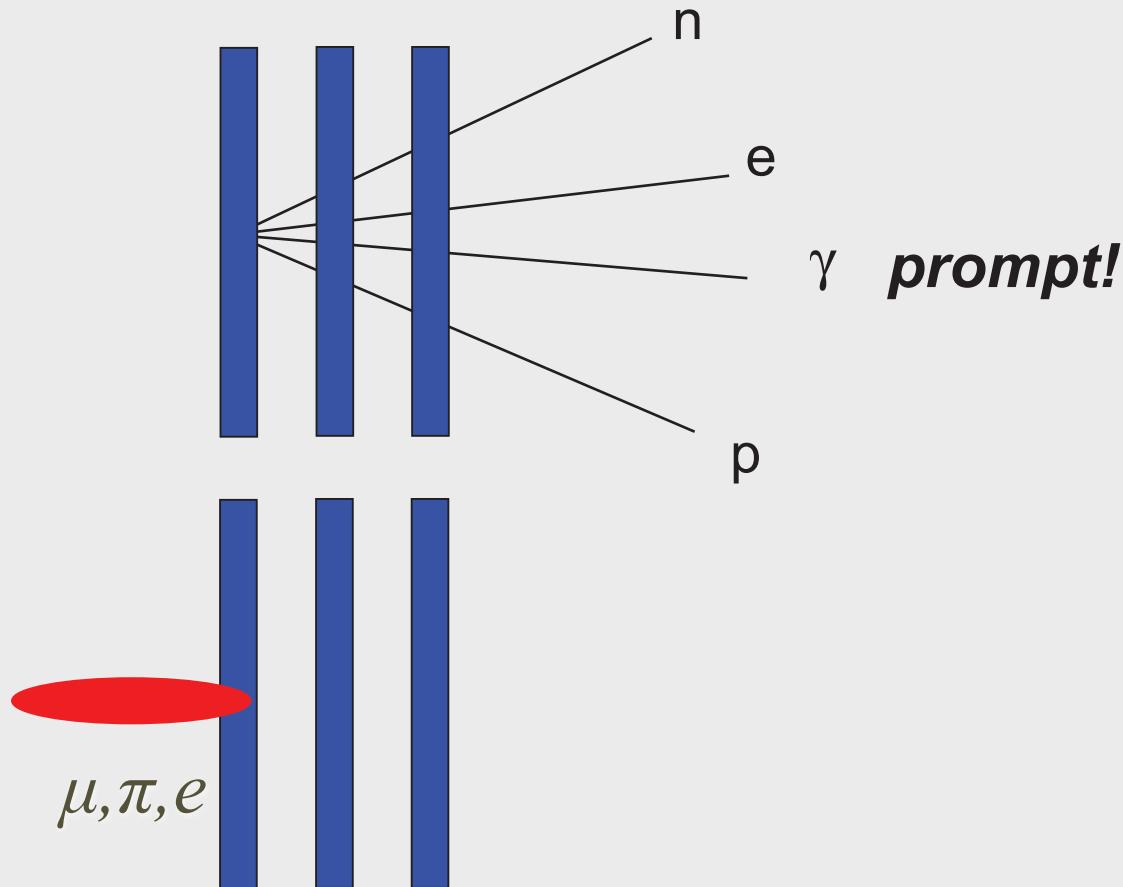
target foils: muon converts here

 = muons, electrons, pions

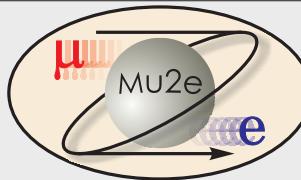
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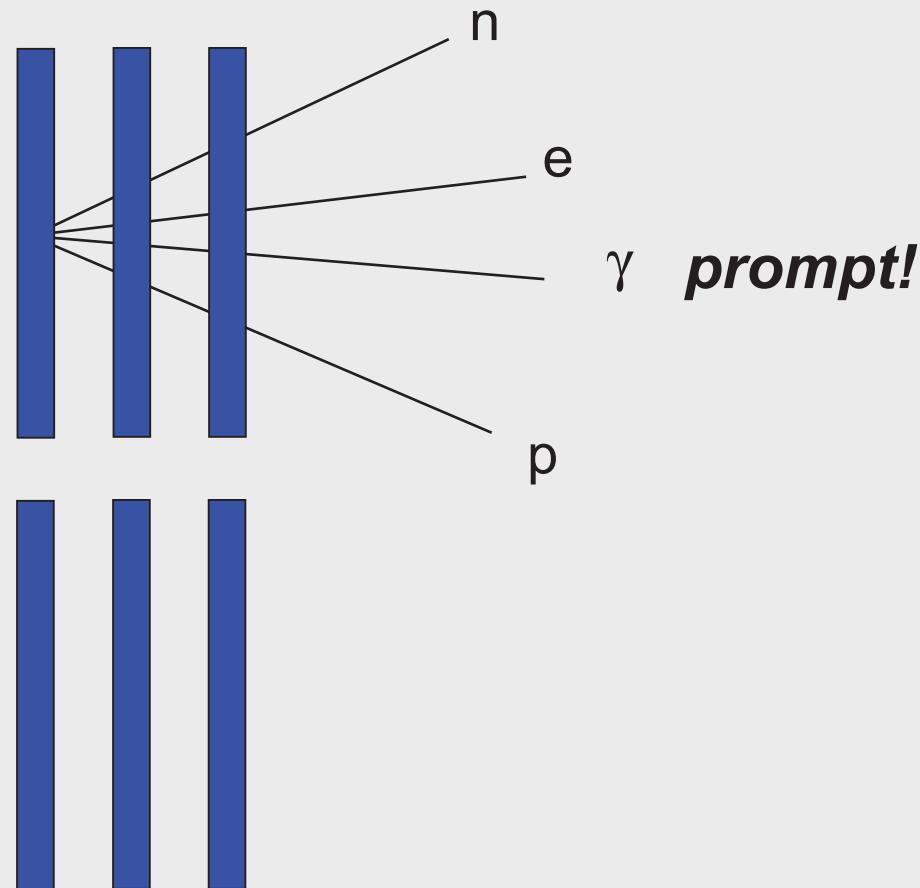
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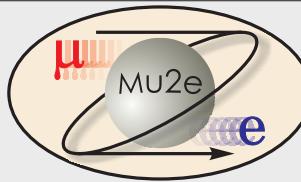


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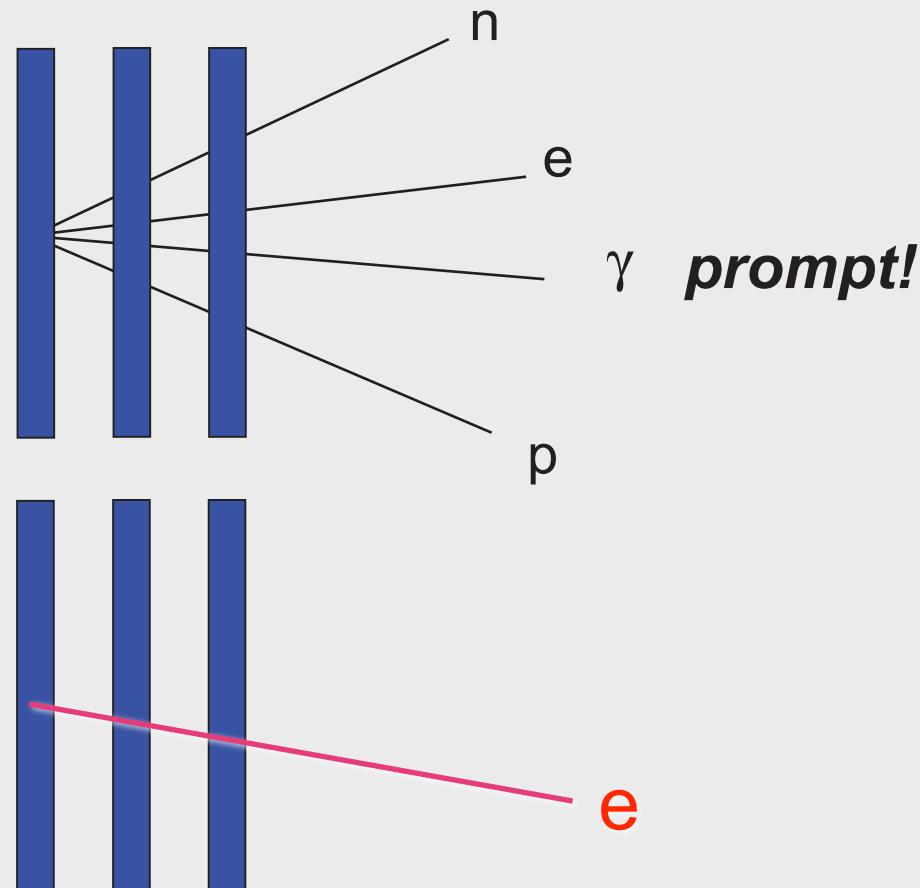
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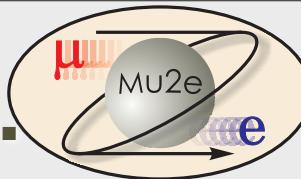
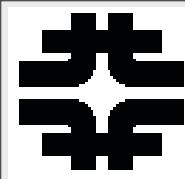
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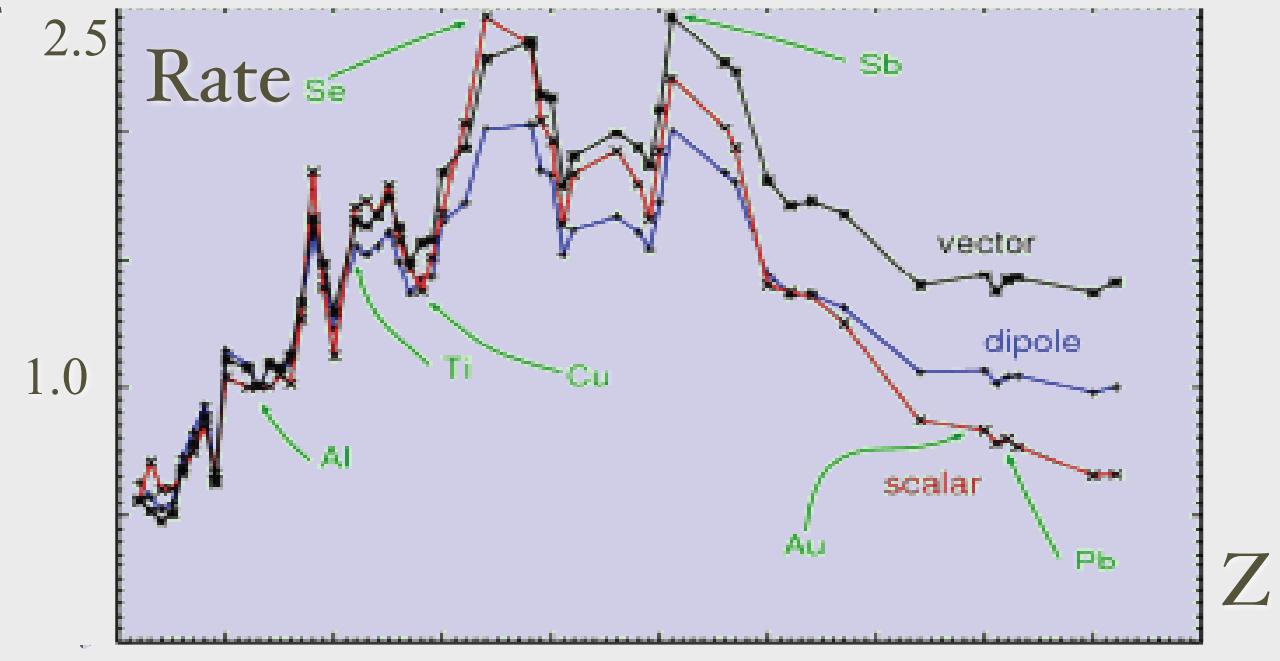
delayed 105 MeV electron



Choice of Stopping Material: rate vs wait

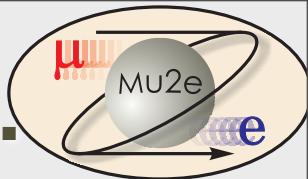
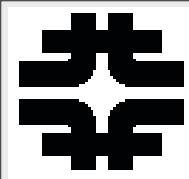
rate normalized to Al

- Stop muons in target (Z, A)
- Physics sensitive to Z : with signal, can switch target to probe source of new physics
- Why start with Al?



Kitano, et al., PRD 66, 096002 (2002)

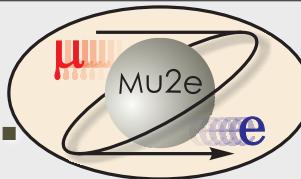
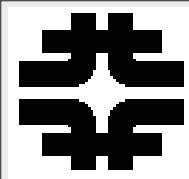
shape governed by relative conversion/capture rate, form factors, ...



Choice of Stopping Material: rate vs wait

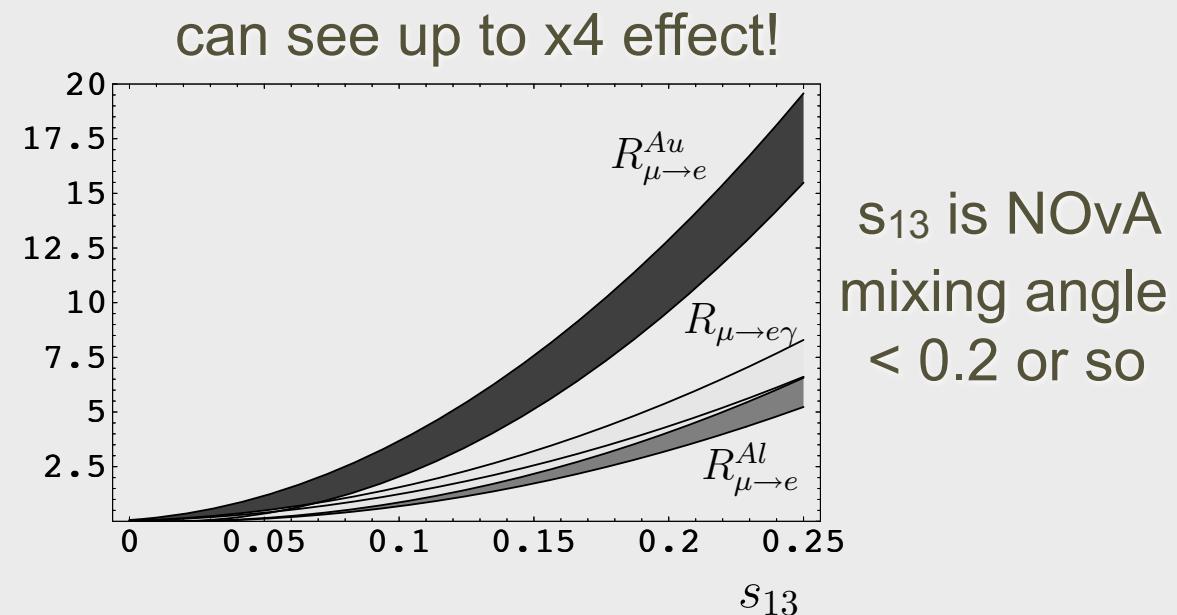
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switch target to
probe source of new
physics
- Why start with Al?

shape governed by relative conversion/capture rate, form factors, ...



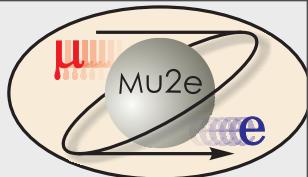
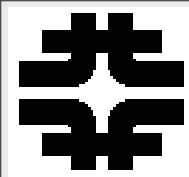
Choice of Stopping Material: rate vs wait

- Stop muons in target (Z, A)
- Physics sensitive to Z : with signal, can switch target to probe source of new physics
- Why start with Al?



V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005.**
e-Print: [hep-ph/0507001](https://arxiv.org/abs/hep-ph/0507001)

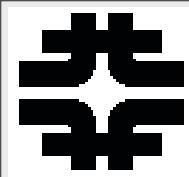
shape governed by relative conversion/capture rate, form factors, ...



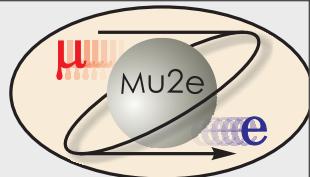
Prompt Background and Choice of Z

choose Z based on tradeoff between rate and lifetime:
longer lived reduces prompt backgrounds

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(\text{Al})$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible



Prompt Background



ch
lo

Nu

Al(

Ti(2

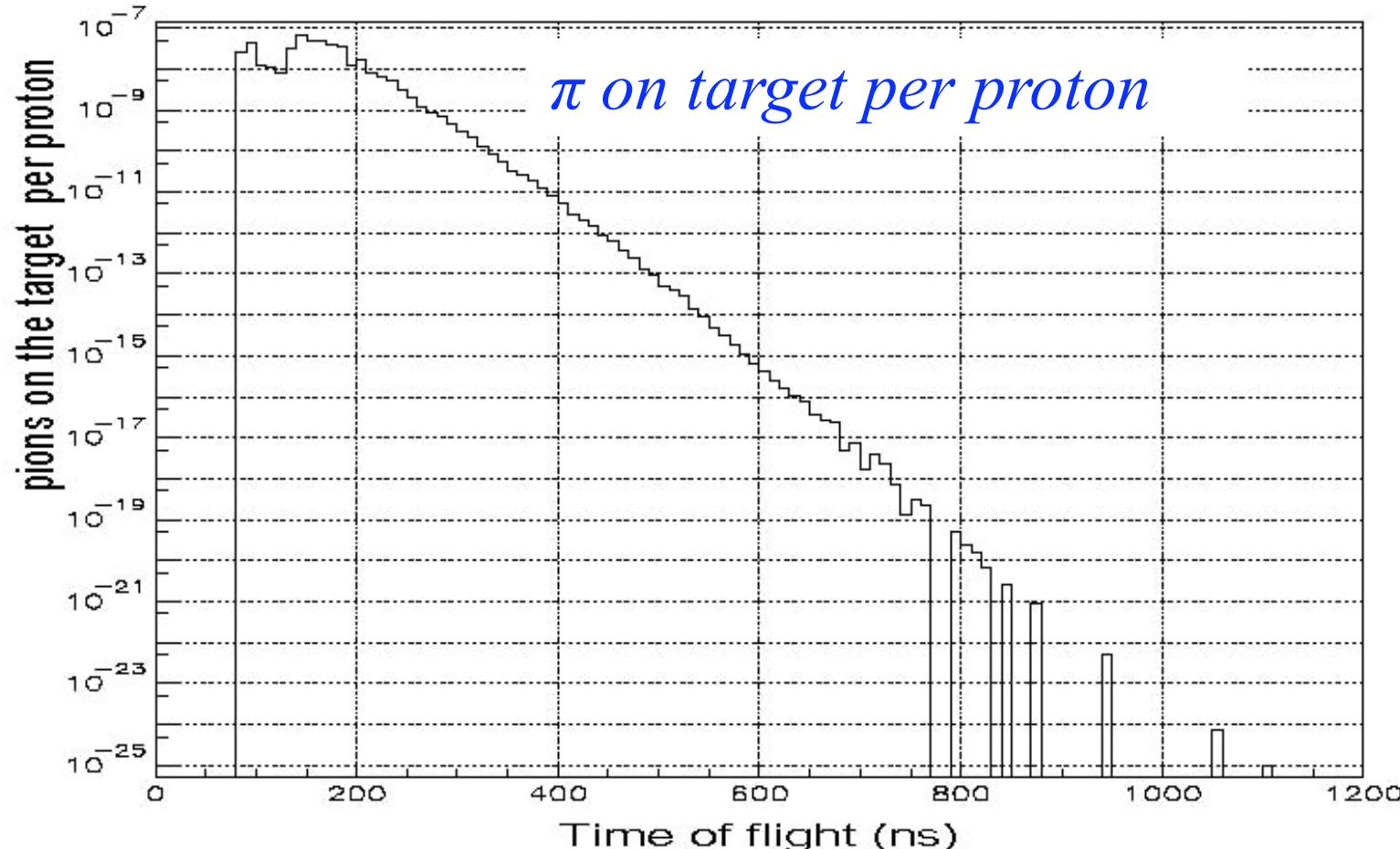
(79,~197)

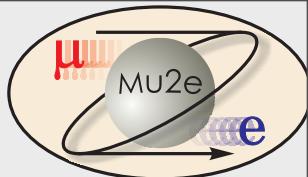
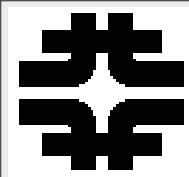
~0.8-1.5

72.6 nsec

MeV

negligible

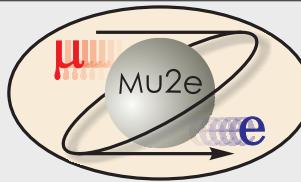
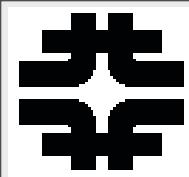




Prompt Background and Choice of Z

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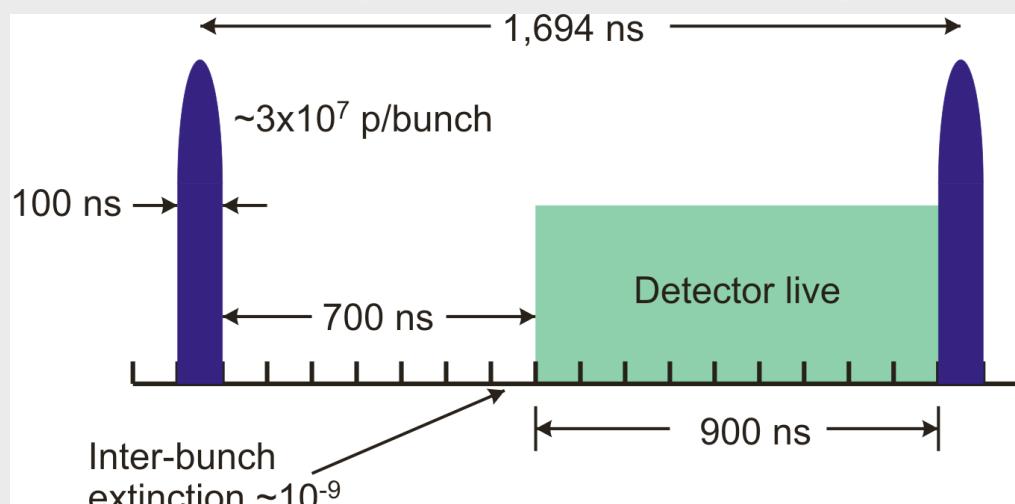


Pulsed Beam Structure

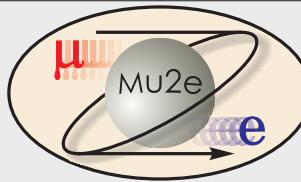
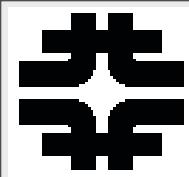
- Tied to prompt rate and machine: FNAL “perfect”
- Want **pulse duration $\ll \tau_\mu^{\text{Al}}$, pulse separation $\approx \tau_\mu^{\text{Al}}$**
- FNAL Debuncher has circumference **$1.7\mu\text{sec}$!**

- Extinction between pulses $< 10^{-9}$ needed

= # protons out of pulse/# protons in pulse



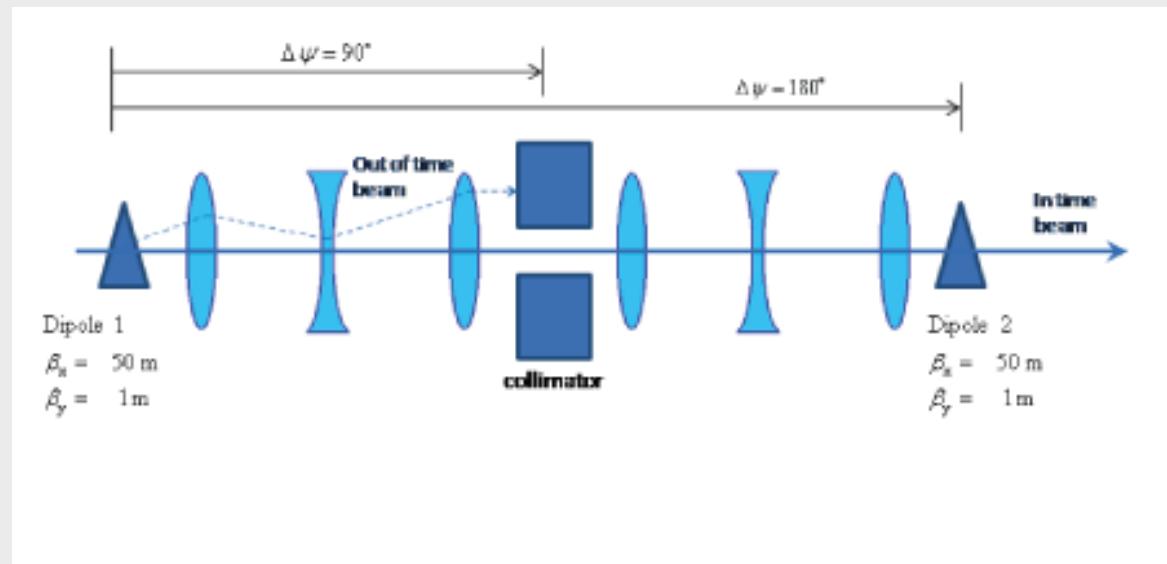
- 10^{-9} based on simulation of prompt backgrounds



Extinction Scheme

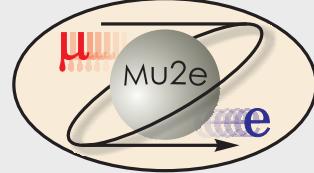
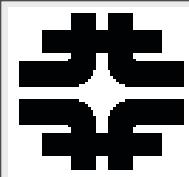
achieving 10^{-9} is hard; normally get $10^{-2} - 10^{-3}$

- Eliminate protons in beam in-between pulses:



CDR under development

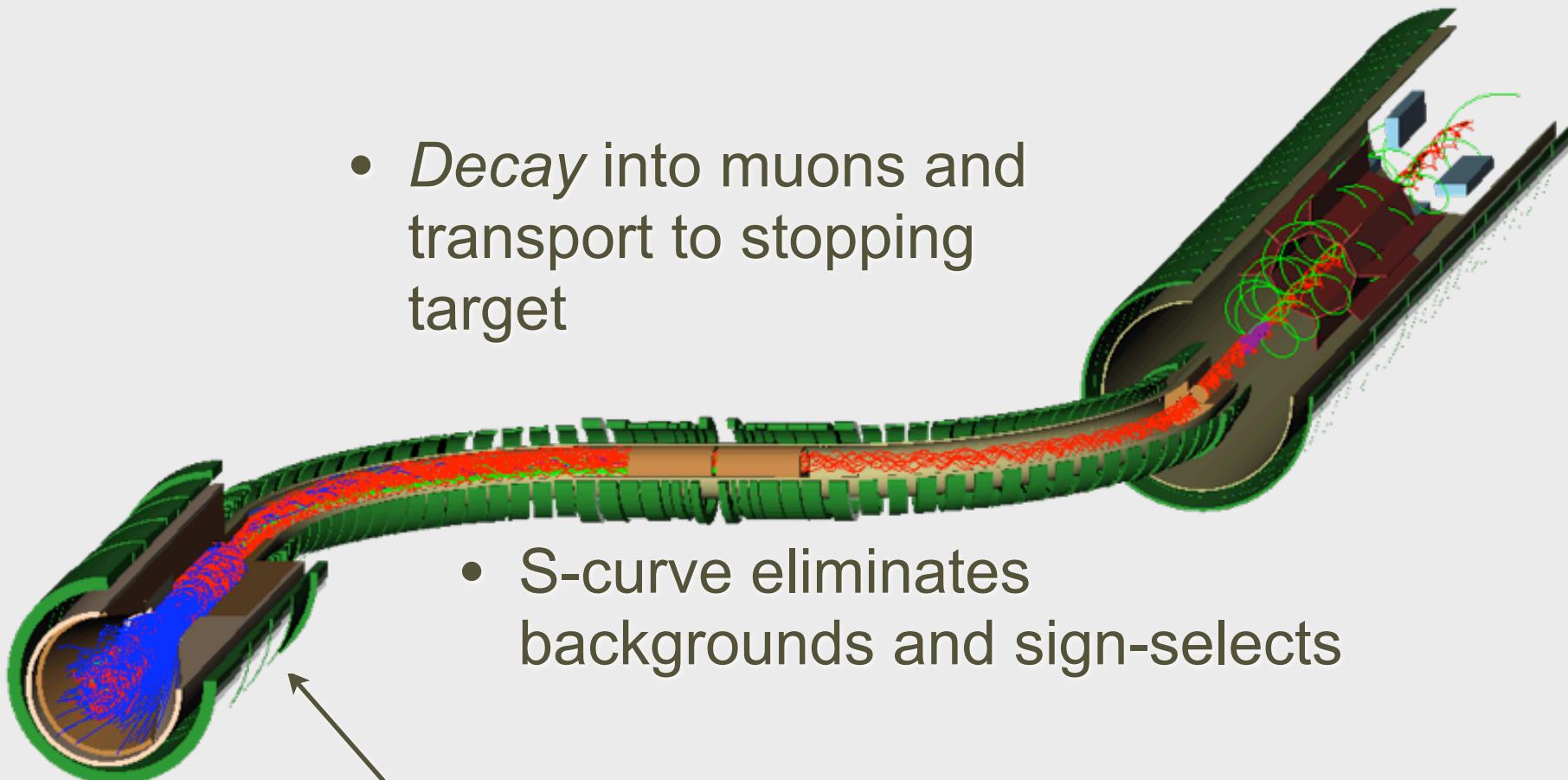
- “Switch” dipole timing to switch signal and background: accept only out-of-time protons for direct *measurement* of extinction
- Continuous Extinction monitoring techniques under study
 - telescope as in MECO
 - (also work at Osaka for COMET)



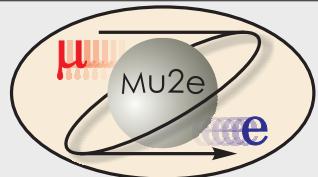
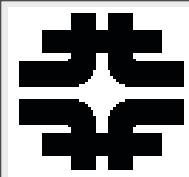
Detector and Solenoid

- *Tracking and Calorimeter*

- *Decay into muons and transport to stopping target*



- *Production: Magnetic bottle traps backward-going π that can decay into accepted μ 's*



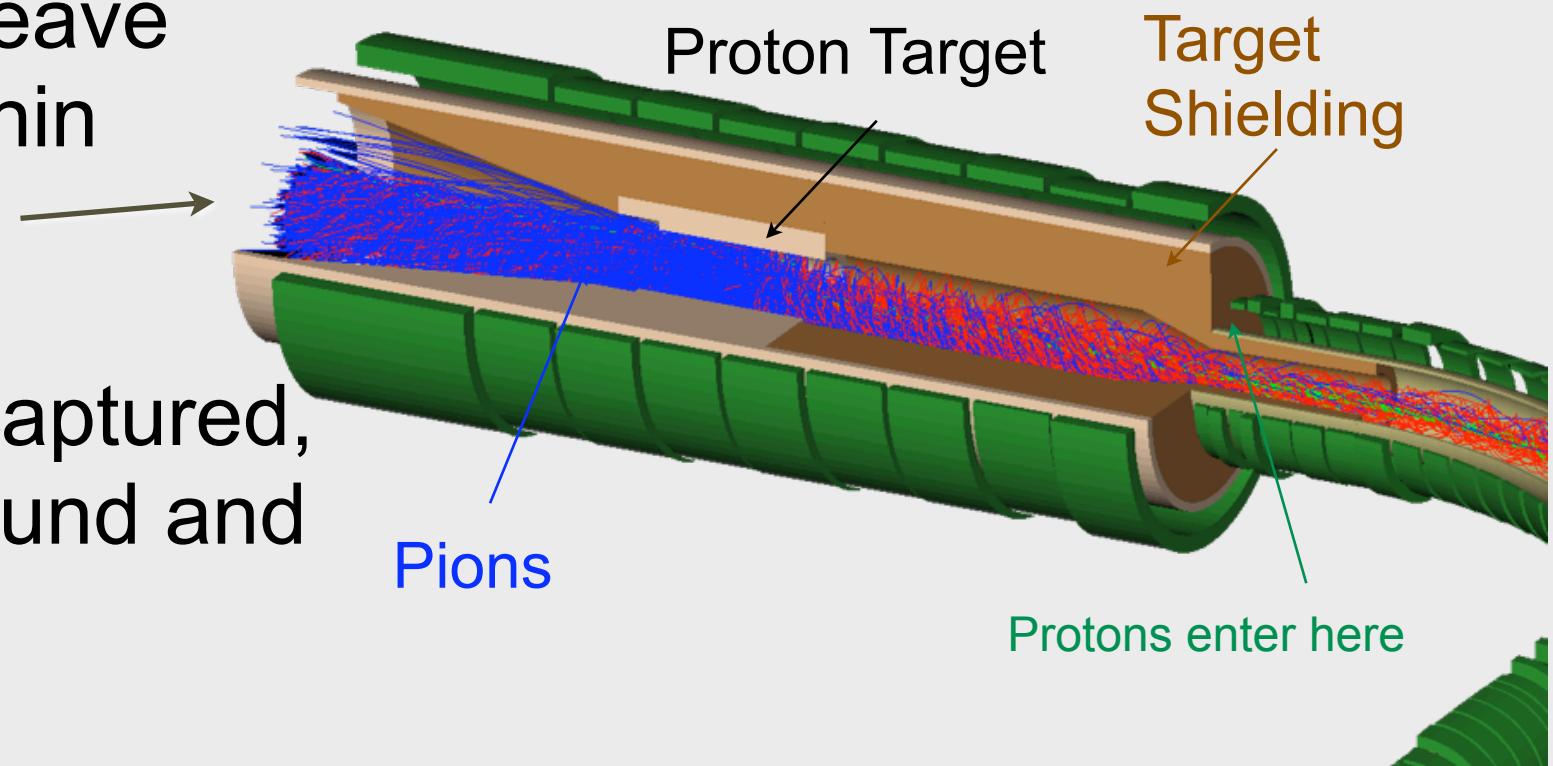
Production Solenoid:

Protons enter opposite to outgoing muons

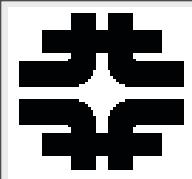
Protons leave
through thin
window

π 's are captured,
spiral around and
decay

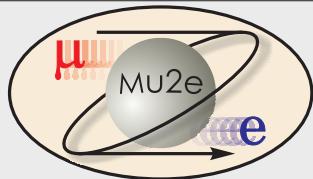
muons exit to right



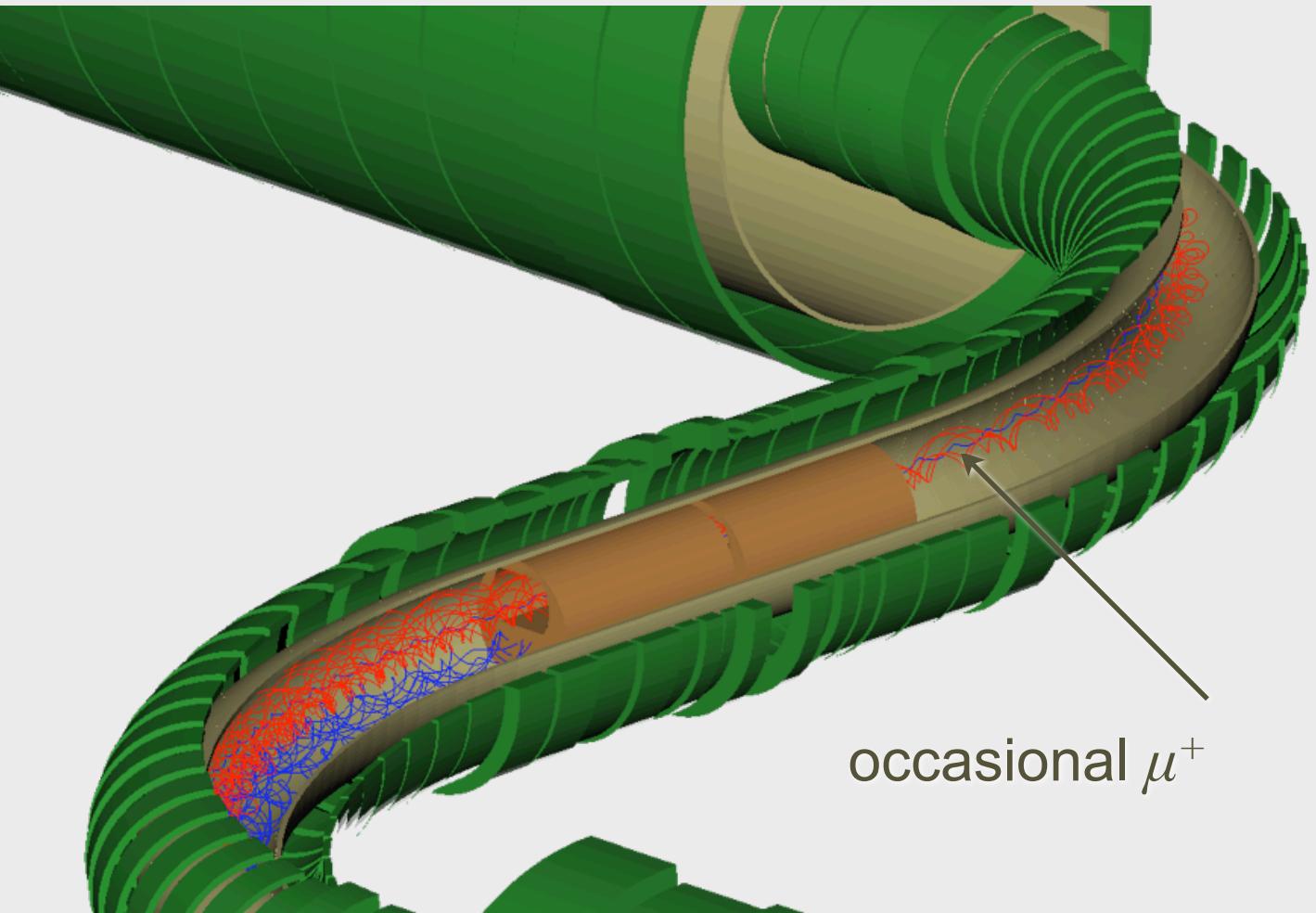
4 m \times 0.30 m



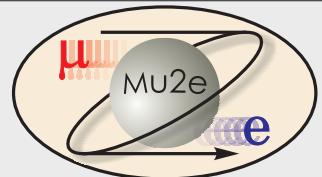
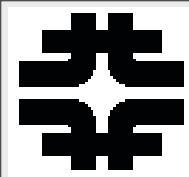
Transport Solenoid



- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam



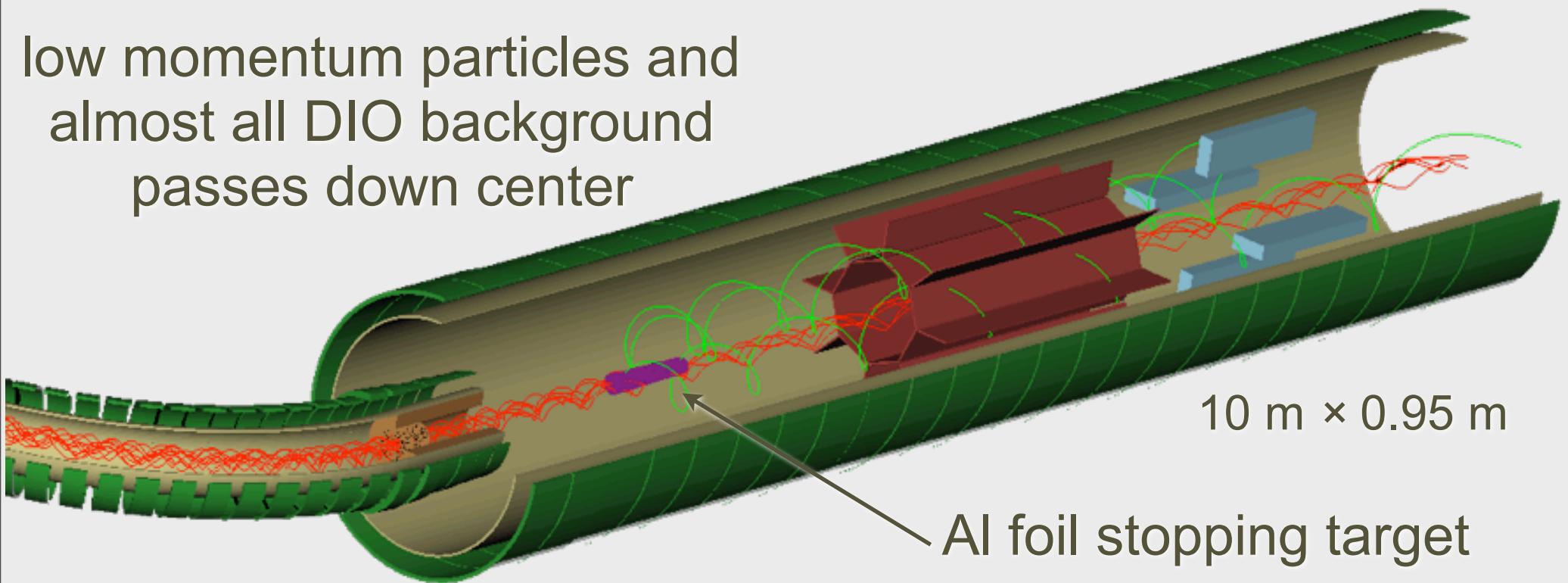
13.1 m along axis $\times \sim 0.25$ m



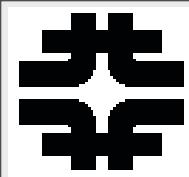
Detector Solenoid

*octagonal tracker surrounding central region:
radius of helix proportional to momentum*

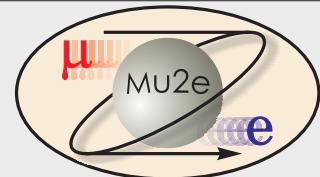
low momentum particles and
almost all DIO background
passes down center



signal events pass *through* octagon of tracker
and produce hits

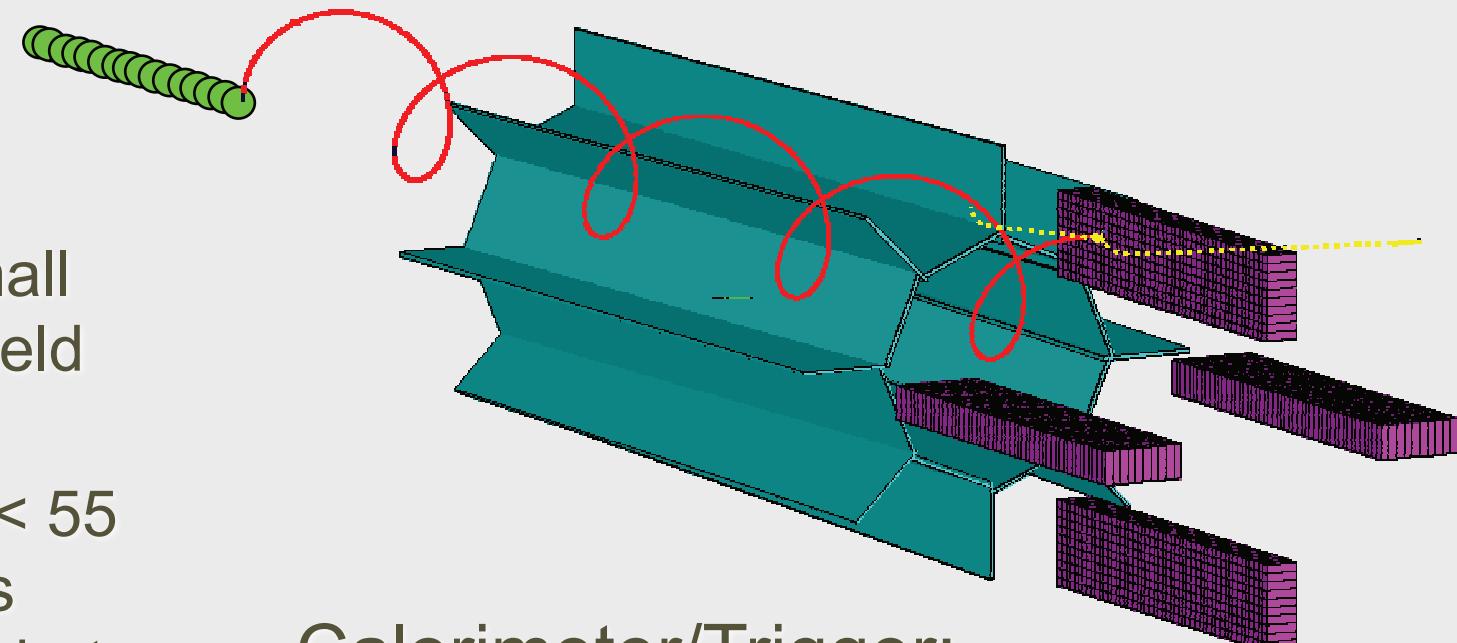


Detector



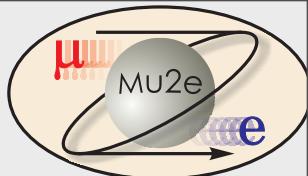
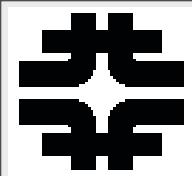
- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
 - up to dE/dx , scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center

$\sigma = 200 \mu$ transverse, 1.5 mm axially
2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick
use return yoke as CR shield



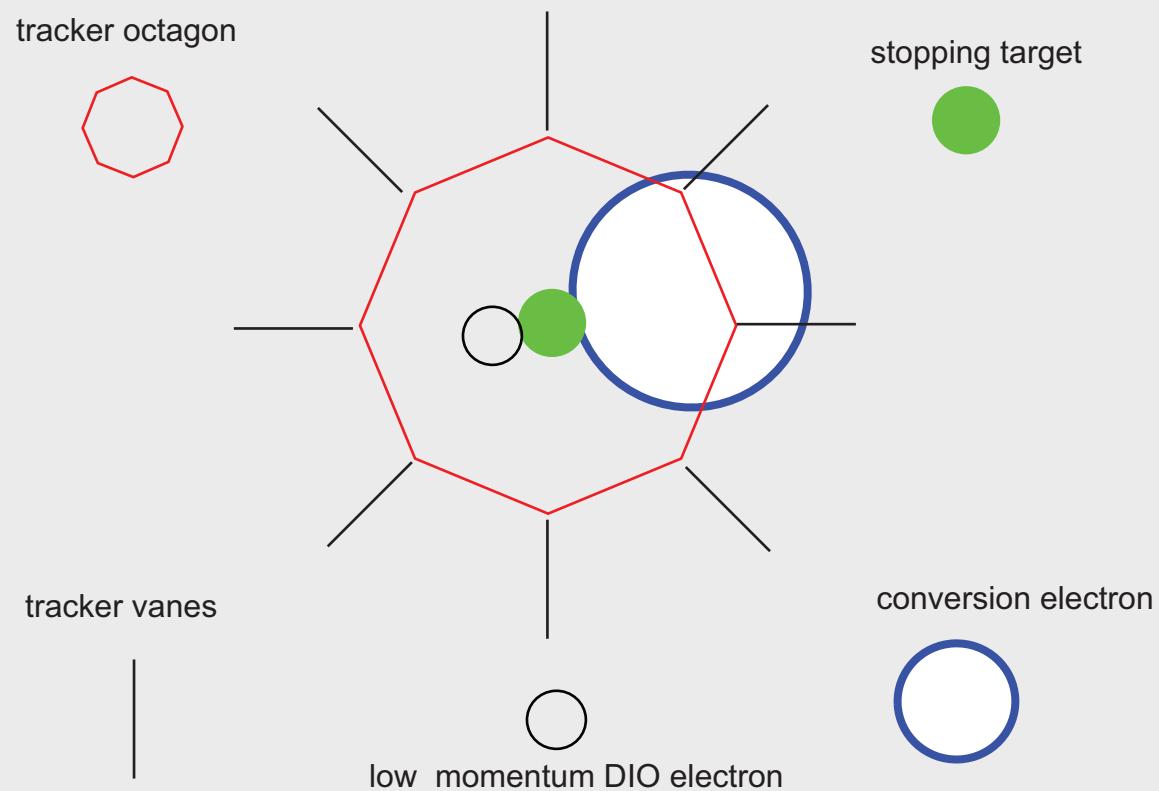
Calorimeter/Trigger:

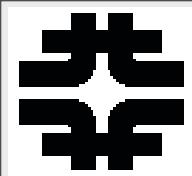
$\sigma / E = 5\%$, 1024 $3.5 \times 3.5 \times 12$ cm PbWO_4



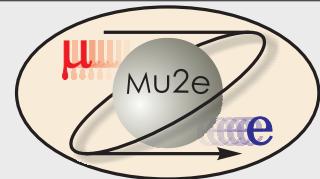
Tracking

- Projection of helical track
- Conversion electron has high momentum (p_T) and has R large enough to pass outside octagon and is tracked
- DIO ($p_T < 55 \text{ MeV}/c$) does not!

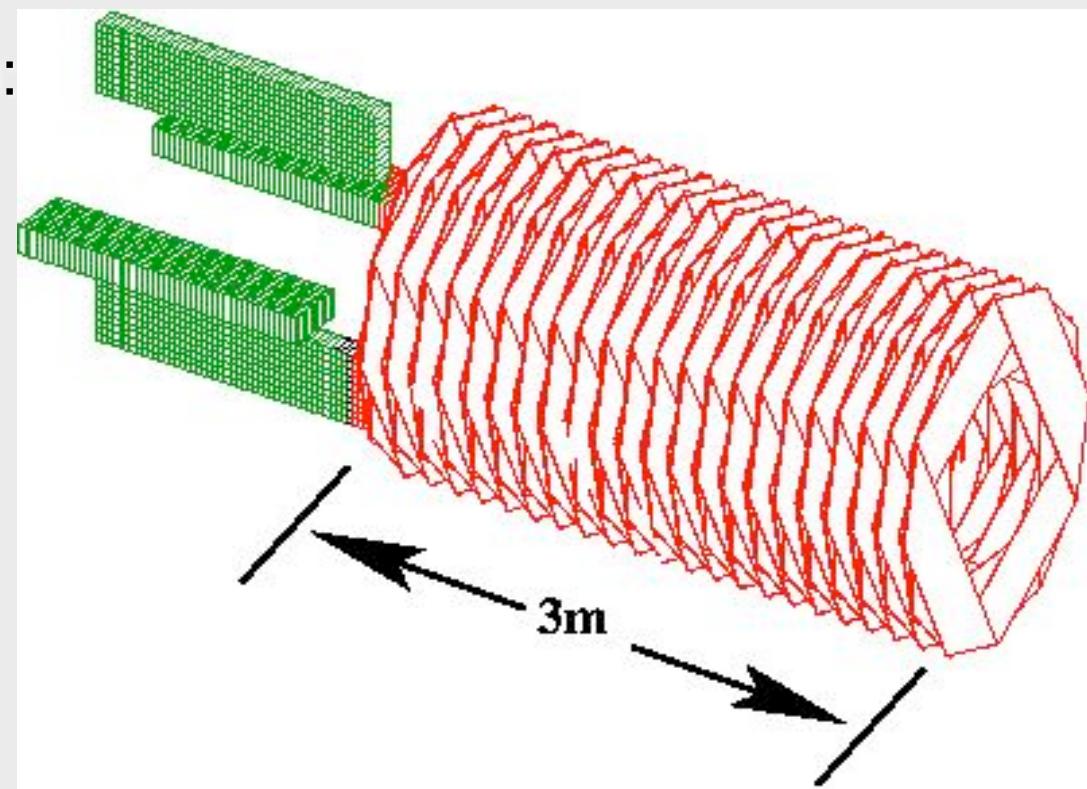
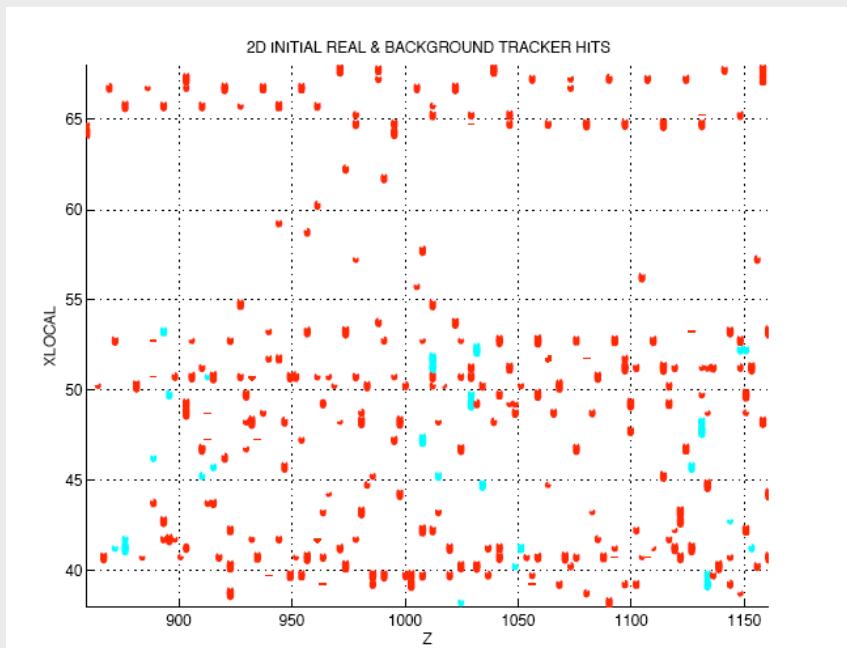




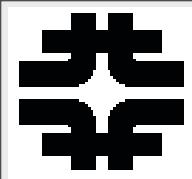
Alternative Tracker



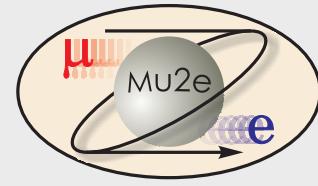
- T-tracker (T for transverse):
- 260 sub-planes
 - sixty 5 mm diameter conducting straws
 - length from 70-130 cm
 - total of 13,000 channels



T-Tracker Pattern Recognition
Difficult but
Kalman Filter is promising

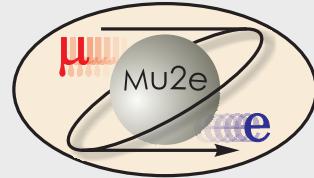
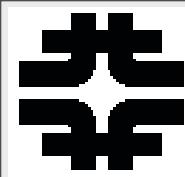


Backgrounds...

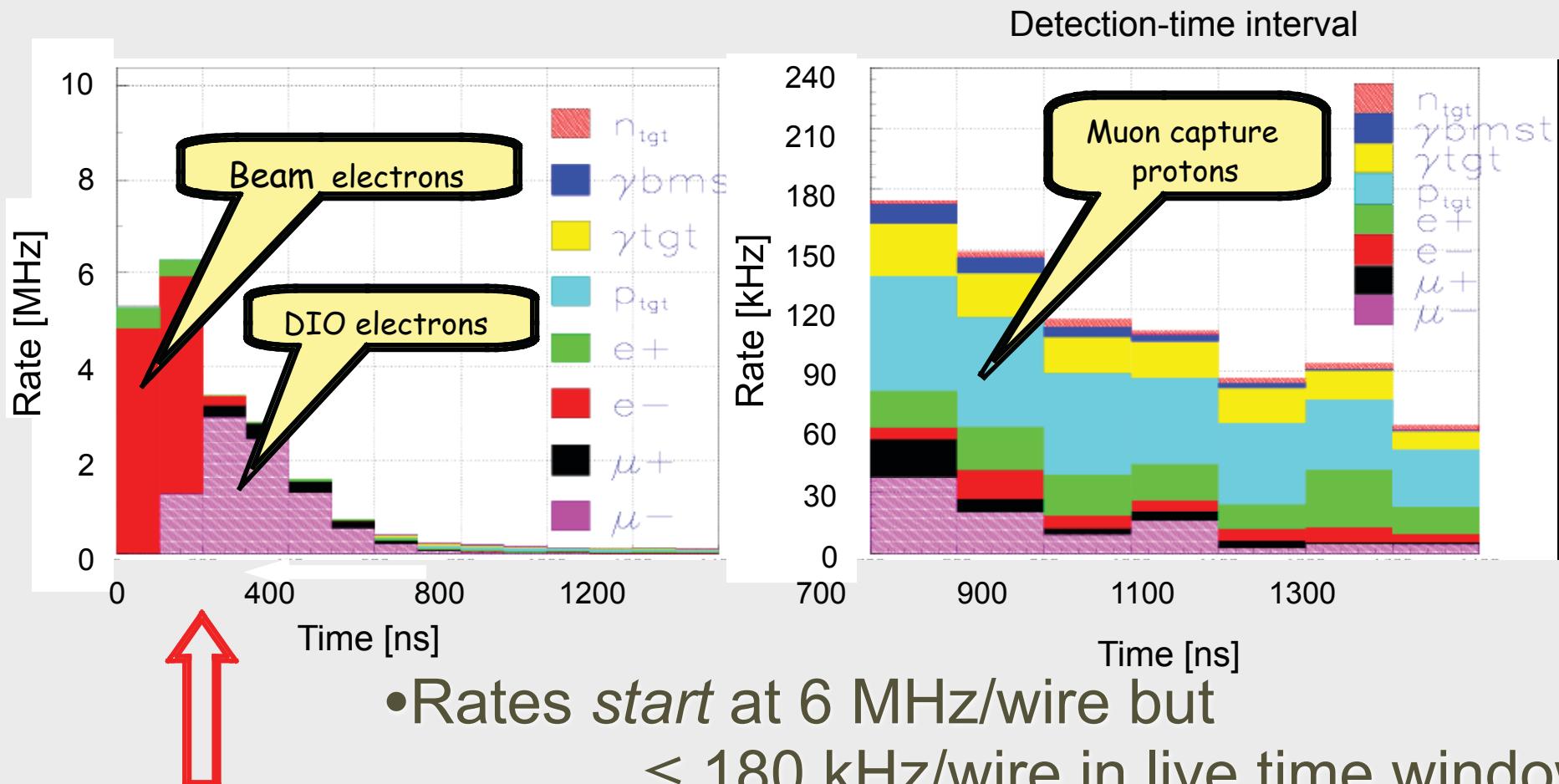


Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, < 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, > 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, < 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, > 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

bd = albedo from beam stop (after calorimeter): flashback, extra hits
confusing pattern recognition

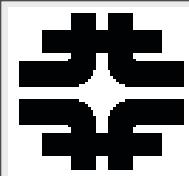


Magnetic Spectrometer: Rates vs. Time

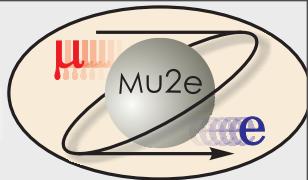


- Rates start at 6 MHz/wire but $\lesssim 180$ kHz/wire in live time window

- Each muon capture produces 2γ , 2n, 0.1p

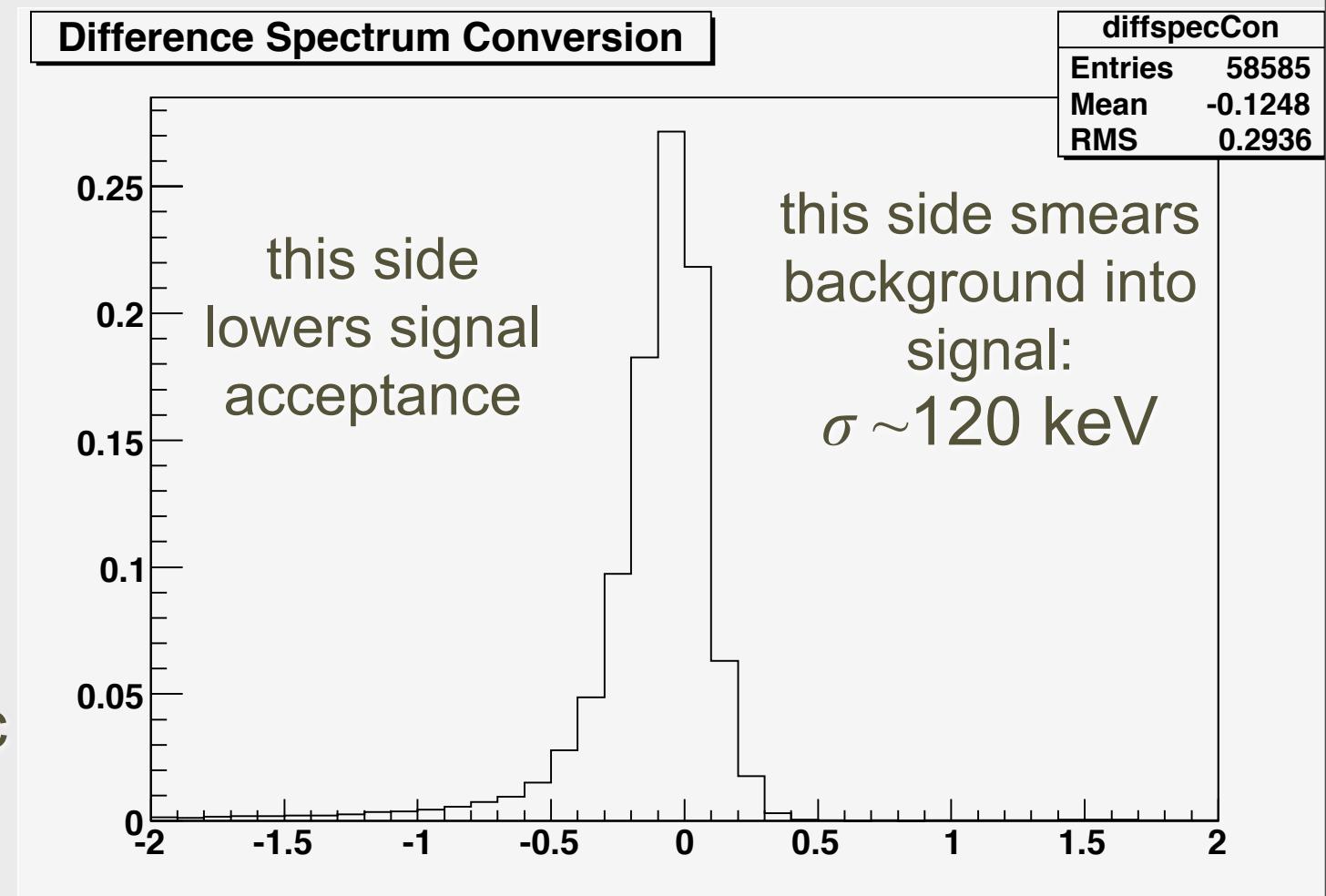


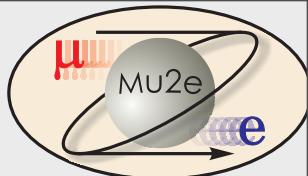
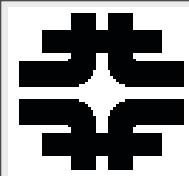
Understanding Resolution



- Measure resolution/
check acceptance:

- special runs
varying target
foils, field,
location of
stopping target
- Use $\pi \rightarrow e\nu$
decay:
monochromatic
line

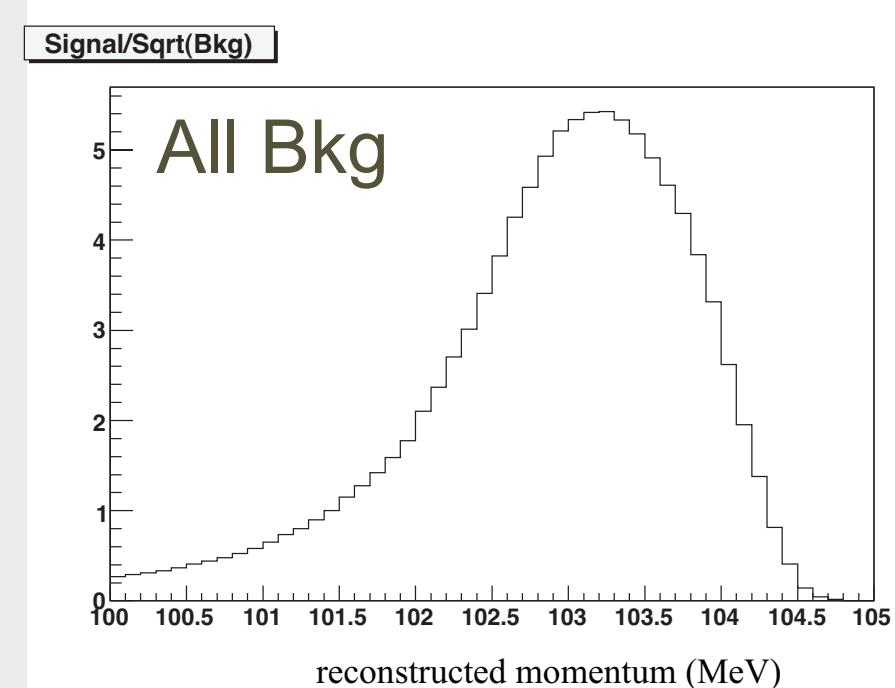
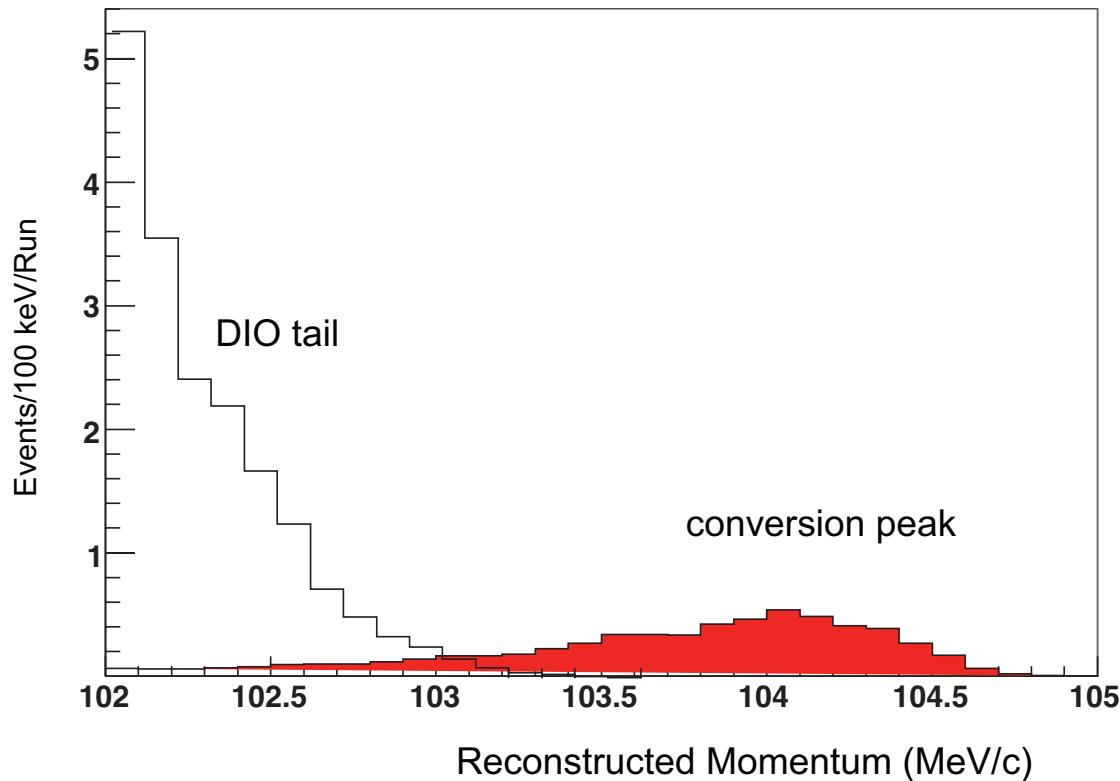




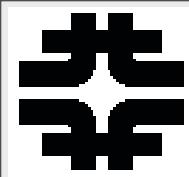
Signal and Background

- $R_{\mu e} = 10^{-16}$

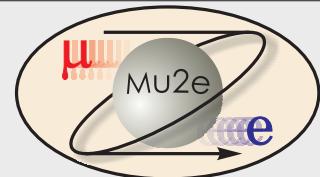
$$\frac{S}{\sqrt{B}} \sim 5.5$$



energy loss in stopping target and other material shifts
electron down to ~ 104 MeV

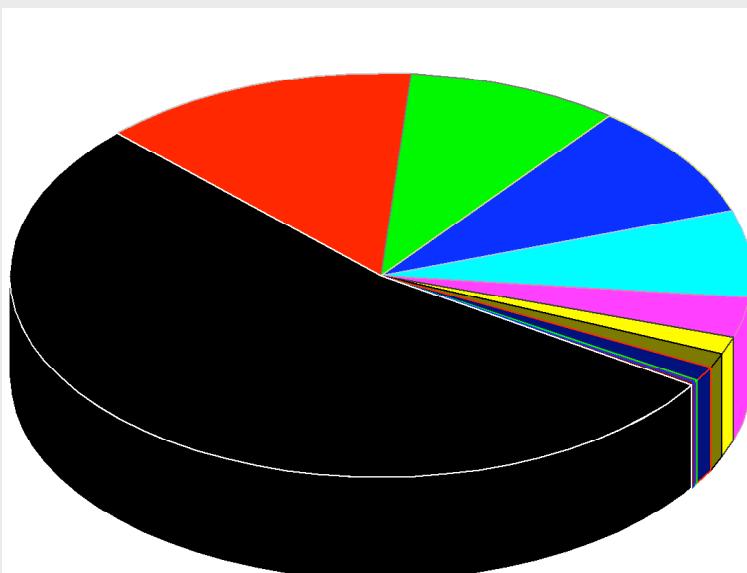


Final Backgrounds

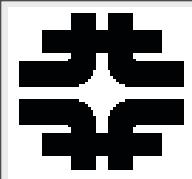


- For $R_{\mu e} = 10^{-15}$
~40 events / 0.4 bkg
(LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
~4 events / 0.4 bkg

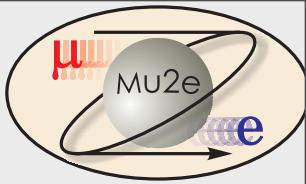
Source	Number
DIO	0.225
Radiative π capture	0.072
μ decay-in-flight	0.072
Scattered e-	0.035
π decay in flight	<0.0035



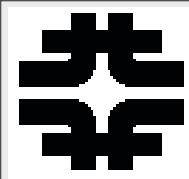
53%: μ decay in orbit
14%: radiative π capture
9%: beam electrons
9%: μ decay in flight (tgt scatter)
< 7%: μ decay in flight (no tgt scatter)
3%: cosmic rays
1.4%: anti-protons
< 1.2%: pattern recognition errors
< 1.2%: radiative μ capture
< 0.2%: π decay in flight
0.2%: radiative π capture from late π 's



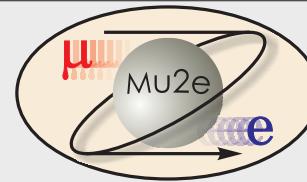
Outline



- The search for muon-electron conversion
- Experimental Technique
- *Fermilab Accelerator*
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



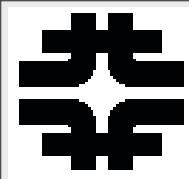
FNAL Beam Delivery



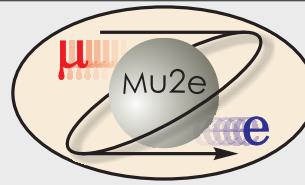
- FNAL has unique, major strength:

Multiple Rings

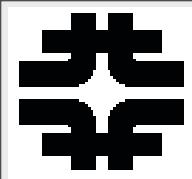
- *no interference* with NOvA neutrino oscillation experiment
- reuse existing rings with only minor modifications



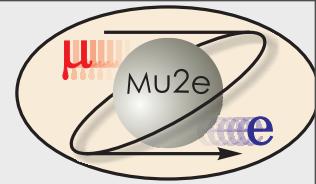
Quick Fermilab Glossary



- Booster:
 - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
 - momentum stacking successive pulses of antiprotons now, 8 GeV protons for Mu2e
- Debuncher:
 - smooths out bunch structure to stack more \bar{p} now; rebunch for Mu2e
- Recycler:
 - holds more \bar{p} than Accumulator can manage, “store” here; transport line for Mu2e



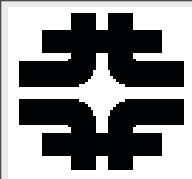
NovA Era and Mu2e



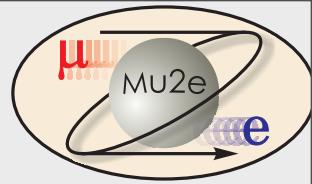
- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

booster batches

- Single-Turn Transfer to MI



NovA Era and Mu2e

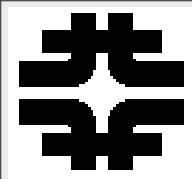


- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

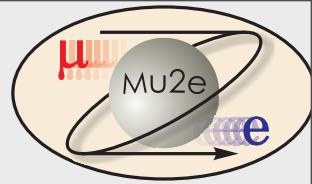


booster batches

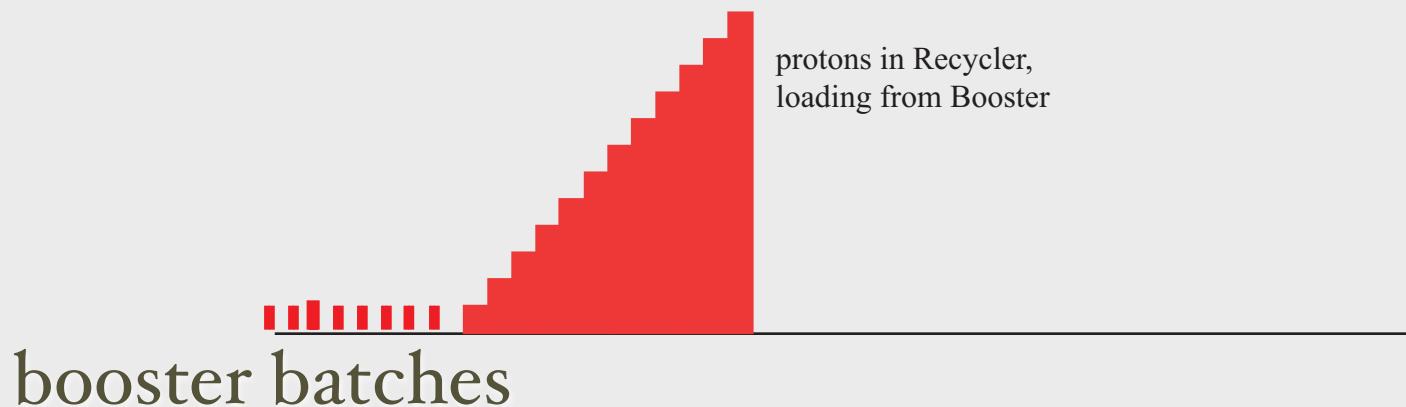
- Single-Turn Transfer to MI



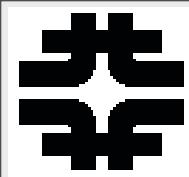
NovA Era and Mu2e



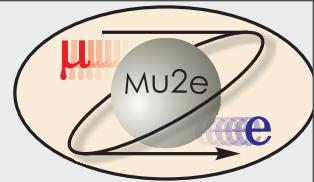
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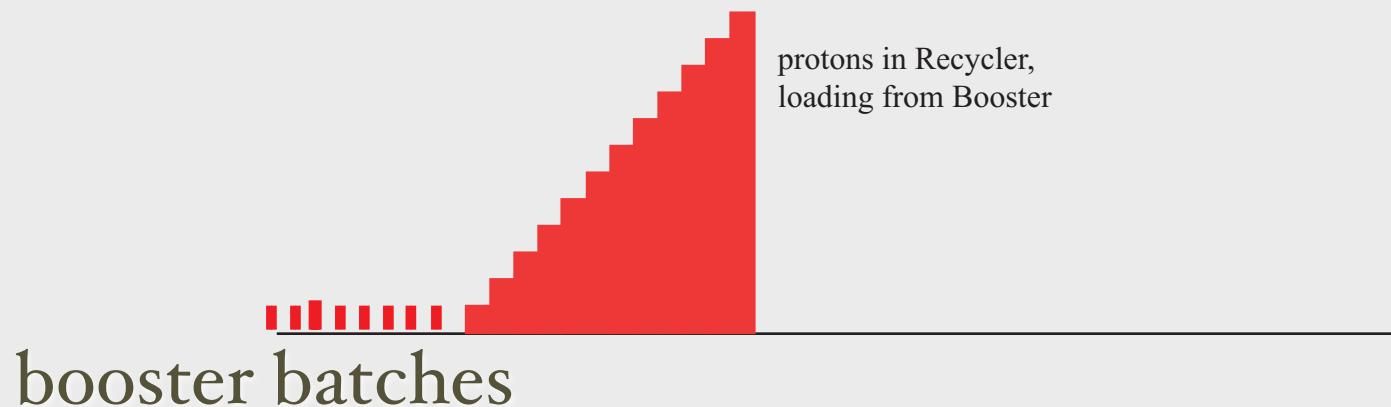
- Single-Turn Transfer to MI



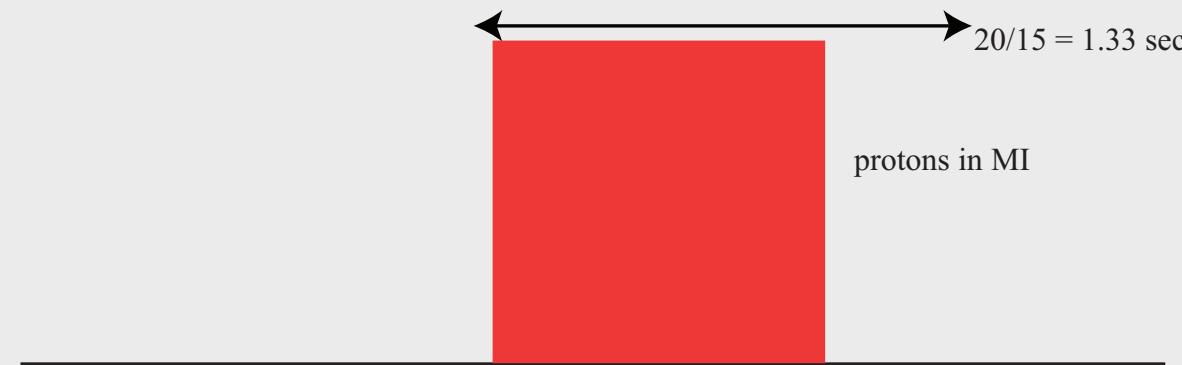
NovA Era and Mu2e

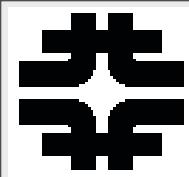


- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

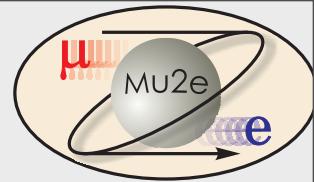


- Single-Turn Transfer to MI

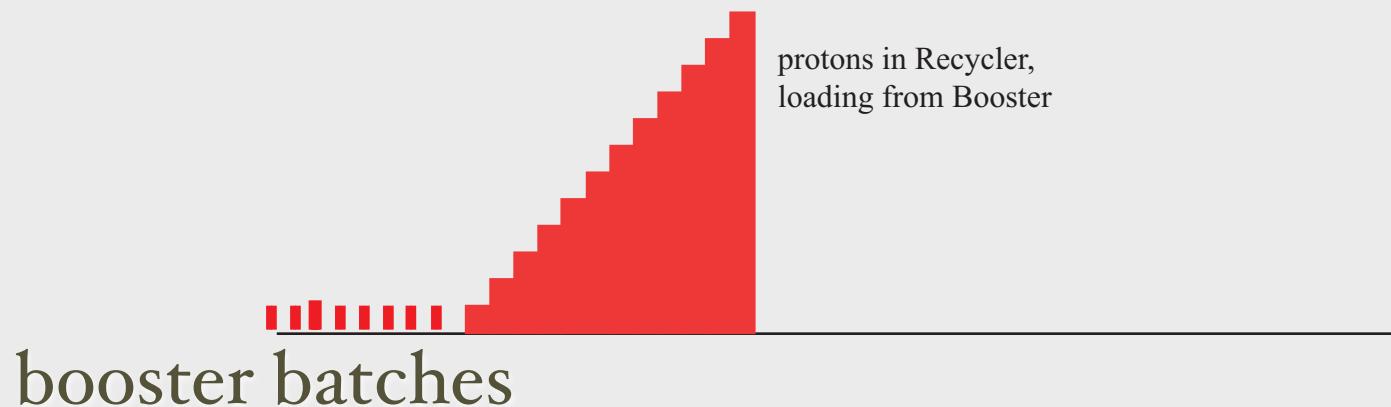




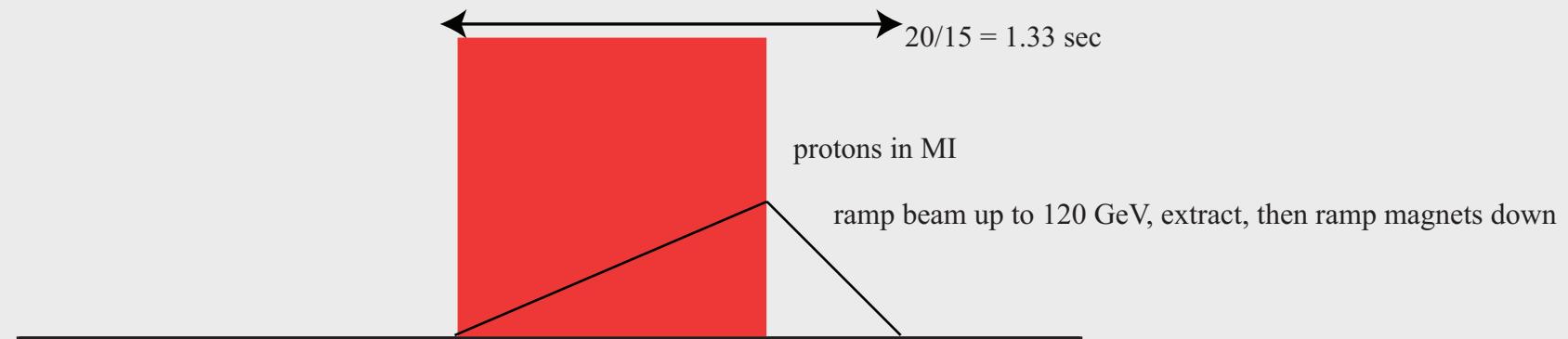
NovA Era and Mu2e

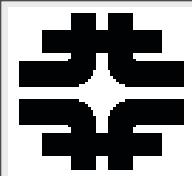


- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

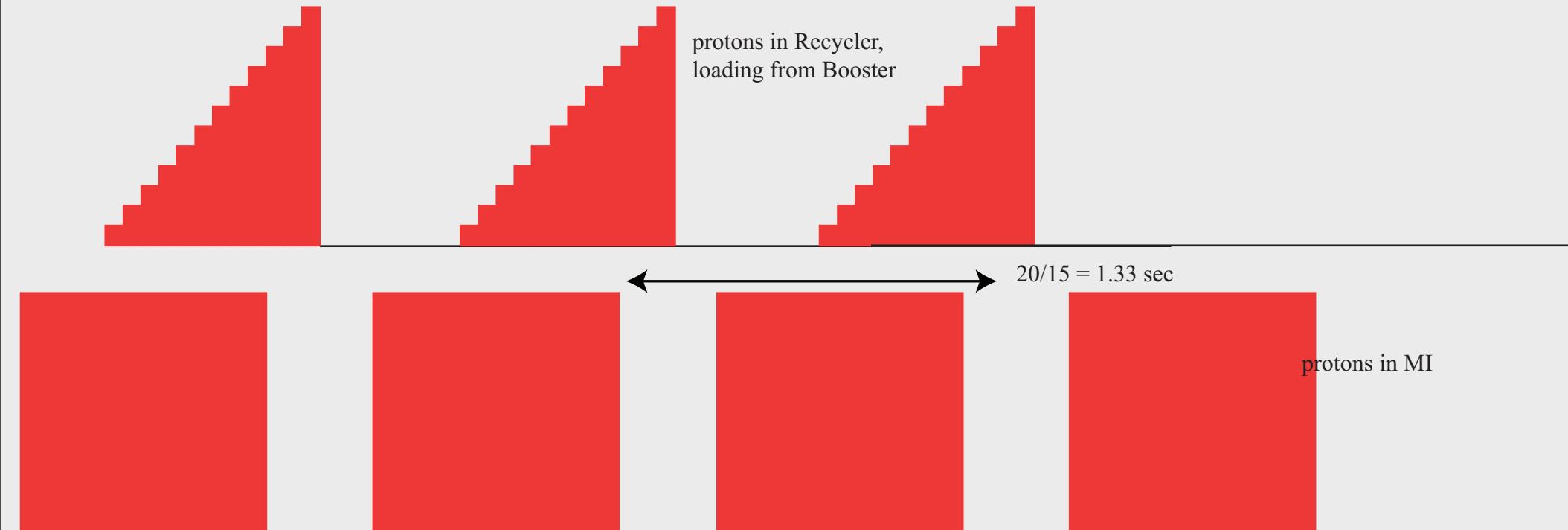
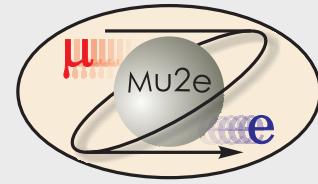


- Single-Turn Transfer to MI





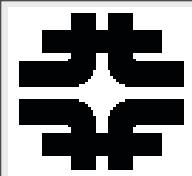
All Together...



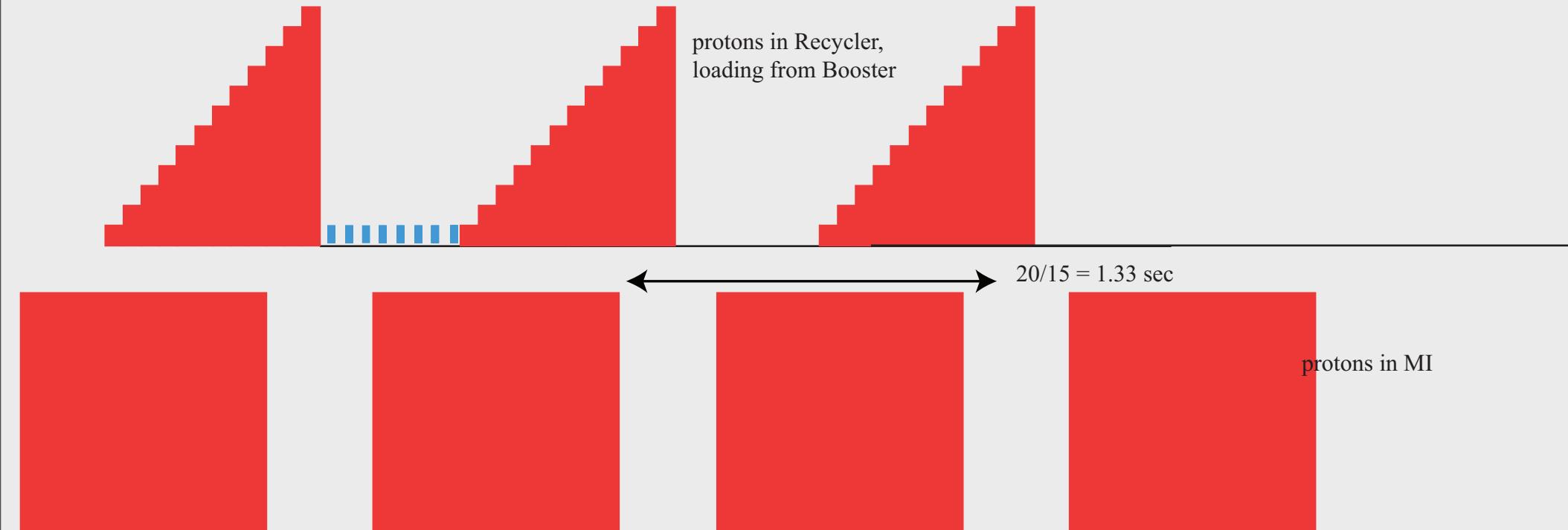
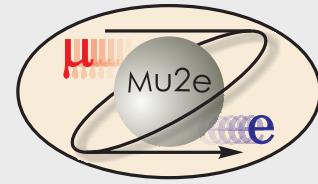
time to ramp allows us to fit eight extra Booster batches for Mu2e
(can use 6)

ramp beam up to 120 GeV, extract, then ramp magnets down



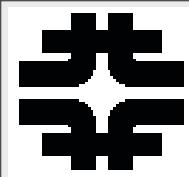


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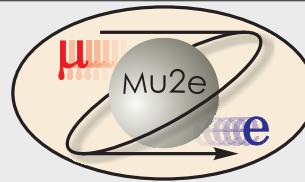


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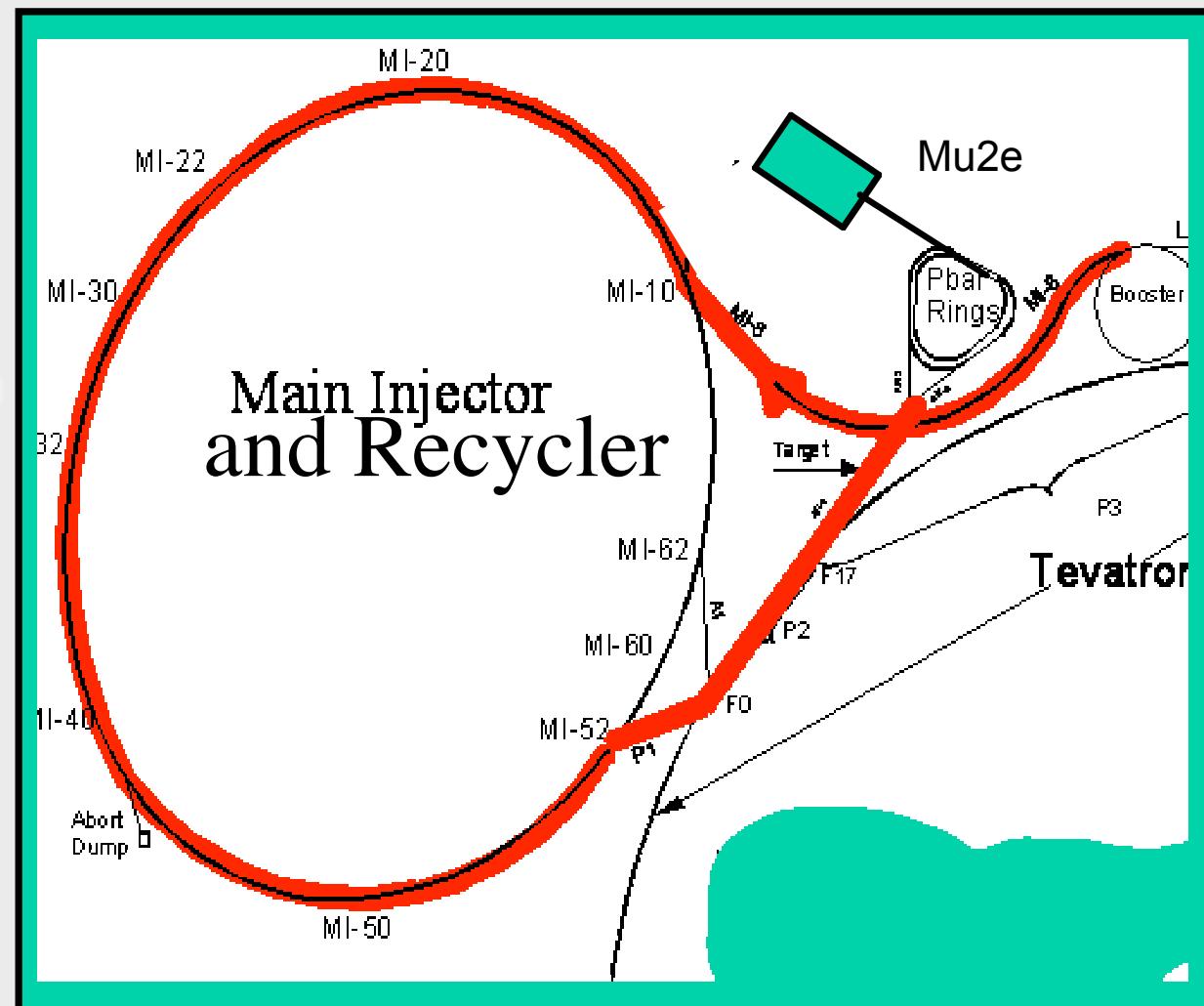
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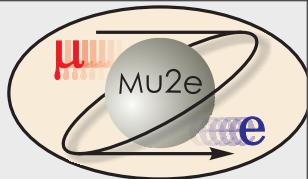
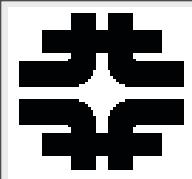


“Boomerang Scheme”



- Booster Batches transported partway through Recycler and injected directly into Accumulator
- “Momentum-Stack” batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
 - 38 nsec RMS, ± 200 MeV
- Slow Extraction: transverse, yields bunch “train”
- Resonant Extraction of Bunch

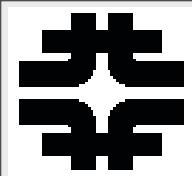




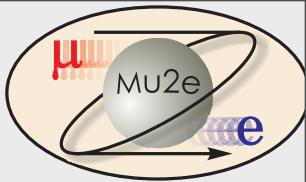
First-Pass Site

- Looking hard at variety of options
- Technical and cost considerations

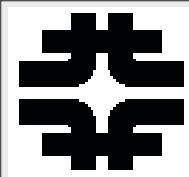




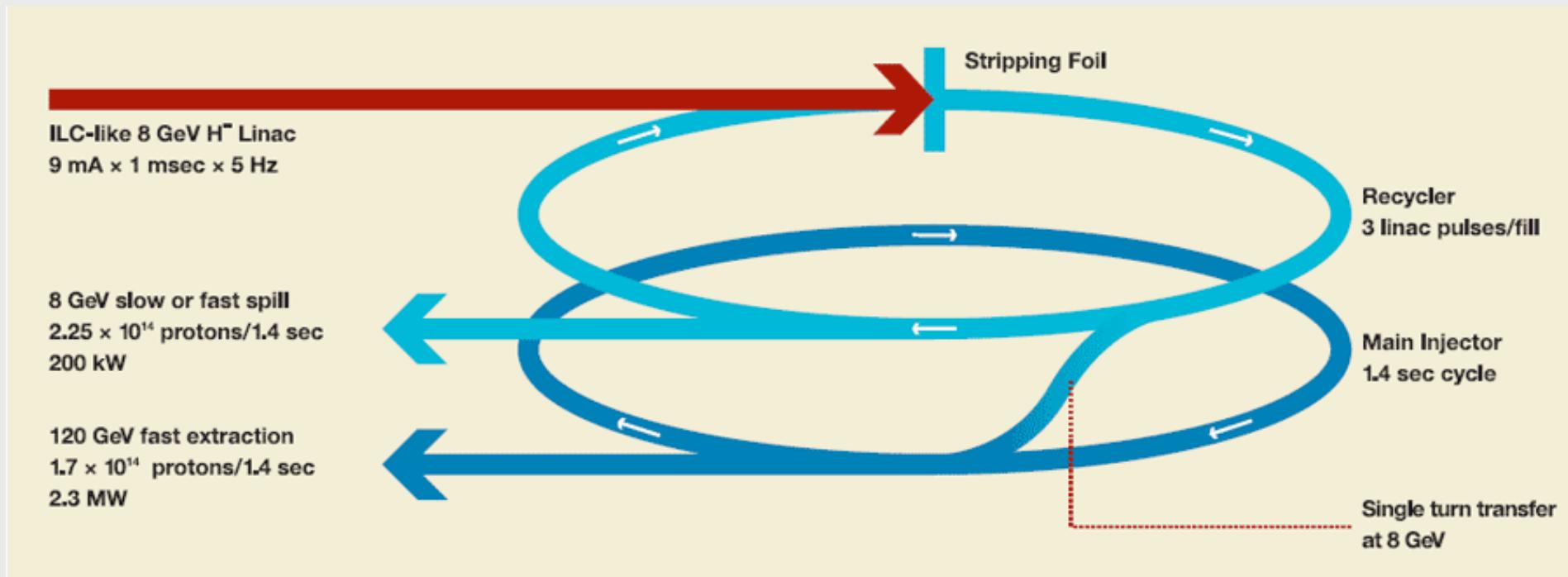
Outline



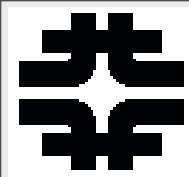
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- *Project X Upgrades and Mu2e*
- Cost and Schedule
- Conclusions



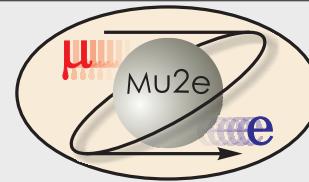
What is Project X?



- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- The source consists of an 8 GeV superconducting linac that injects into the Fermilab Recycler



Mu2e and Project X



*available 8 GeV Power
for intensity frontier*

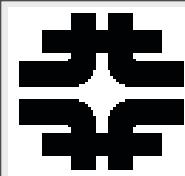
- First establish a signal or set a strong limit -- what do we do next?
- Project X gives us a chance to upgrade the experiment by up to x100

20 kW
(current)

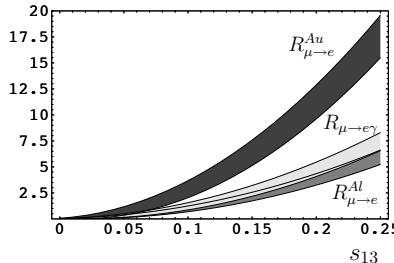
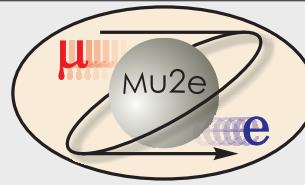
200 kW
(Project X)

2000 kW

(Project X Upgrades)



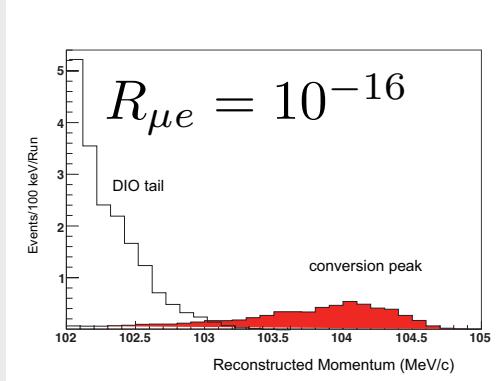
Upgrade Plans...



Yes

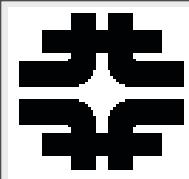
Signal?

No

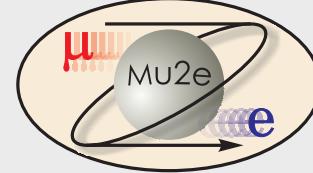


1. Change Z of Target to determine source of new physics
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

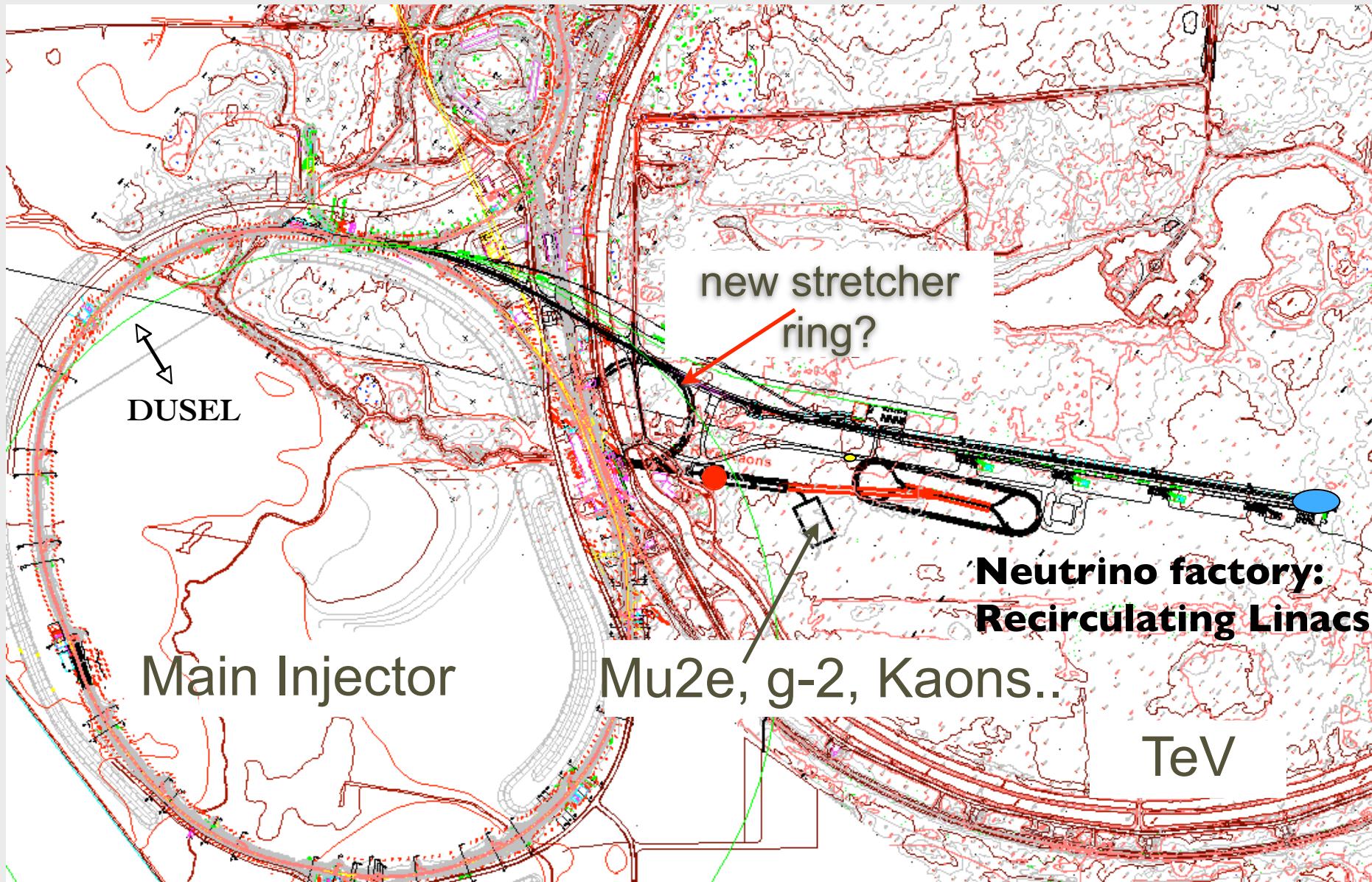
1. Both Prompt and DIO backgrounds must drop to measure $R_{\mu e} \sim 10^{-18}$
2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

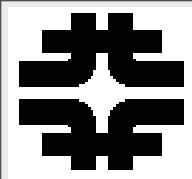


Project X Era?

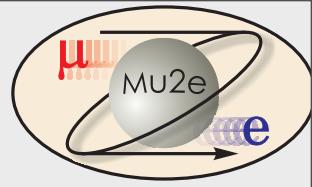


not approved or part of any official plan...

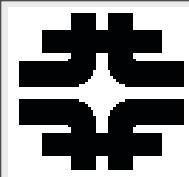




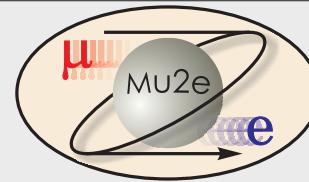
Outline



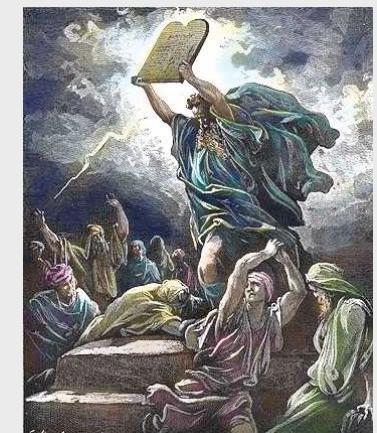
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- Conclusions



Cost and Schedule

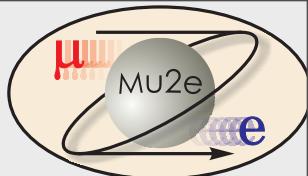
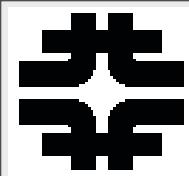


- *This is a technically limited schedule*
- Critical Path is Superconducting Solenoids
- \$190M “fully-loaded” Total Cost



Solenoids	2009				2010				2011				2012				2013				2014				2015				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Conceptual Design																													
Final Design/place contracts																													
Construction/installation/commissioning																													

data-taking 1st quarter Calendar 2016



What Does This Mean?

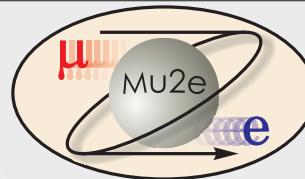
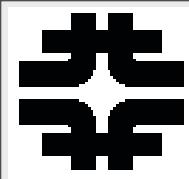
design, prototyping, test beams...

Solenoids	2009				2010				2011				2012			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Conceptual Design																
Final Design/place contracts																
Construction/installation/commissioning																

busy measuring beam, detector properties, ...

2013				2014				2015				2016			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

background studies final data-taking

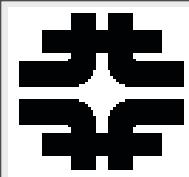


US Gov't DOE CD Process

Lasciate ogne speranza, voi ch'intrate



Inferno
fresco in Camposanto, Pisa

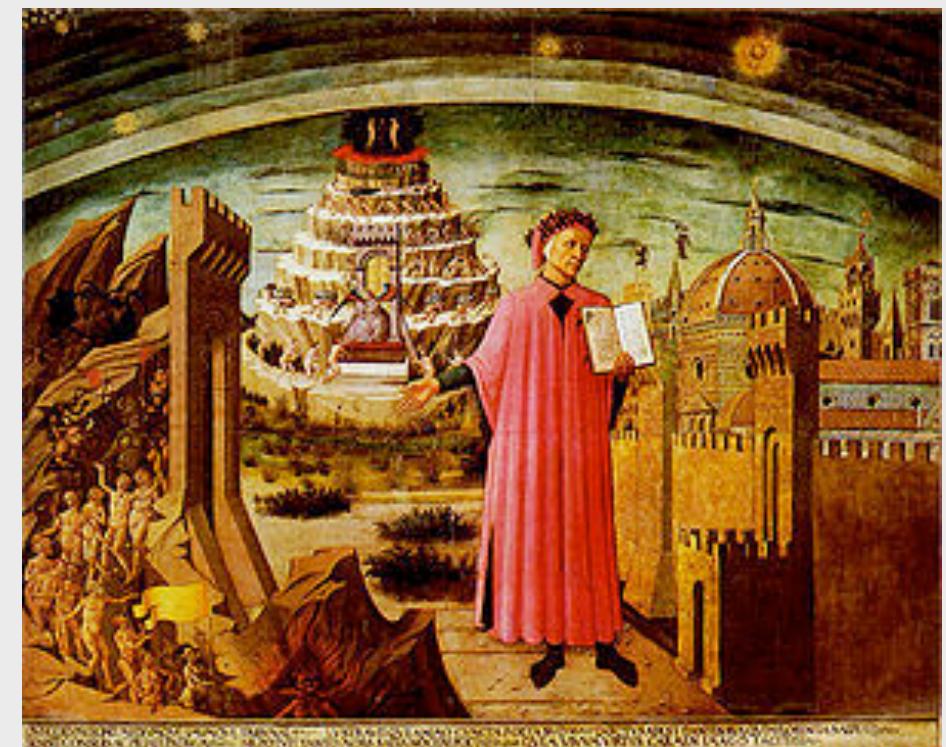


US Gov't DOE CD Process

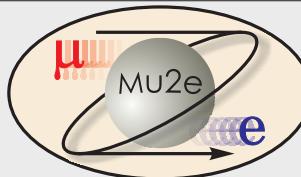
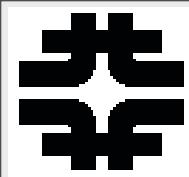
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CD
process



US Gov't DOE CD Process

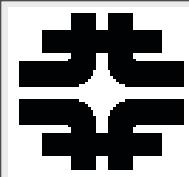
Lasciate ogne speranza, voi ch'intrate

Experimenter's
Reward

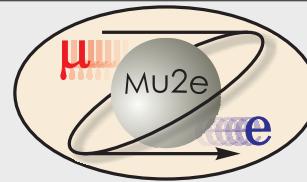


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fresco in Camposanto, Pisa

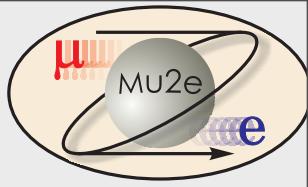
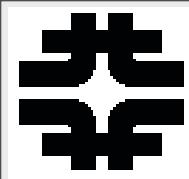
CD
process



Guide to DOE CD Process

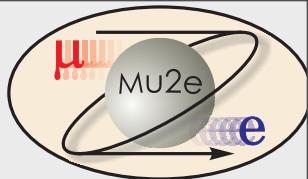
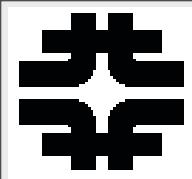


- CD–0: “mission need”
 - the DOE decides this is part of its goals and then DOE prepares document
 - ***DOE: Feb 2009 for Mu2e***
- CD–1: “conceptual design”
 - careful, systematic evaluation of alternatives
 - cost and schedule well along but not final
- CD–2: “baseline” / technical design
 - firm cost and schedule estimates for entire experiment
- CD–3: *spend money!*

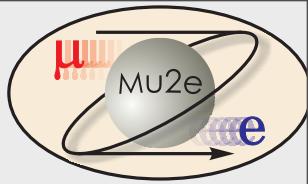
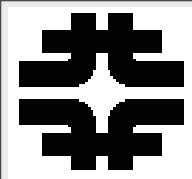


Conclusions

- Mu2e will either:
 - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)*
 - *Discover unambiguous proof of Beyond Standard Model physics and*
 - *Provide important information either complementing or probing up to 10^4 GeV mass scales*
- With upgrades, we could extend the limit by up to two orders of magnitude or study the details of new physics



And Perhaps Answer Rabi's Question about the physics of flavor and generations



And Perhaps Answer Rabi's Question about the physics of flavor and generations



Who ordered that?